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THE EVER-CHANGING CIRCUMSTELLAR NEBULA AROUND UW CENTAURI

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ABSTRACT

We present new images of the reflection nebula surrounding the R Coronae Borealis Star, UW Centauri. This nebula, first detected in 1990, has changed its appearance significantly. At the estimated distance of UW Cen, this nebula is approximately 0.6 lt-yr in radius, so the nebula cannot have physically altered in only 8 years. Instead, the morphology of the nebula appears to change as different parts are illuminated by light from the central star that is modulated by shifting thick dust clouds near its surface. These dust clouds form and dissipate at irregular intervals, causing the well-known declines in the R Coronae Borealis (RCB) stars. In this way, the central star acts like a lighthouse shining through holes in the dust clouds and lighting up different portions of the nebula. The existence of this nebula provides clues to the evolutionary history of RCB stars, possibly linking them to the planetary nebulae and the final helium shell flash stars.

Subject headings: circumstellar matter — stars: individual (UW Centauri) — stars: variables: other

1. INTRODUCTION

R Coronae Borealis (RCB) stars are a small group of hydrogen-deficient carbon-rich supergiants that undergo spectacular declines (ΔV up to 8 mag) at irregular intervals apparently tied to their pulsation cycles (Clayton 1996). A cloud of carbon-rich dust forms and temporarily eclipses the photosphere, revealing a rich "chromospheric" emission spectrum, and then it disperses, allowing the star to return to maximum light. The dust is thought to form in patches or puffs, not as a complete shell. Only when the dust condenses in the line of sight will a deep decline occur, although clouds may form during every pulsation cycle somewhere over the surface of the star. Thus, the events are irregular and unpredictable. Extensive ground- and space-based observations of R CrB, RY Sgr, and V854 Cen have pointed to a unified empirical model of the RCB decline (see Clayton 1996 and references therein). A close connection between the pulsational phase and the time of dust formation—seen in RY Sgr and V854 Cen—implies that condensation occurs near the star (Pugach 1977; Lawson et al. 1992, 1999). Observed timescales for the radiative acceleration of the dust, the eclipse of the chromospheric region, and the dispersal of the dust add further support to the "near-star" model.

There are two major evolutionary models for the origin of RCB stars: the double degenerate and the final helium shell flash (Iben, Tutukov, & Yungelson 1996). The former involves the merger of two white dwarfs, and in the latter, a white dwarf/evolved planetary nebula (PN) central star is blown up to supergiant size by a final helium shell flash. In the final flash model, there is a close relationship between RCB stars and PNs. The connection between RCB stars and PNs has recently become stronger, since the central stars of three old PNs (Sakurai's object, V605 Aql, and FG Sge; Duerbeck & Benetti 1996; Clayton & De Marco 1997; Gonzalez et al. 1998; Kerber 1998; Kerber et al. 1999) have had observed outbursts that transformed them from hot evolved central stars into cool giants with the spectral and dust formation properties of an RCB star. This establishes a possible connection between RCB stars, central stars of PNs, and the final flash scenario. On the other hand, there is evidence that after the final flash, a central star acquires RCB characteristics only for a short time: V605 Aql was an RCB star in 1921, but by 1986 it appeared to have a much hotter spectrum $T_{\rm eff} \sim 50{,}000$ K (Clayton & De Marco 1997). If most final flash stars evolve very rapidly, this scenario for the formation of RCB stars may not be able to yield the number of observed RCB stars. Moreover, the recent claim that white dwarf merging times might not be as long as previously thought has made the double-degenerate scenario a valid and appealing alternative to the final flash scenario for the formation of RCB stars (Iben et al. 1996).

So the presence or absence of nebulae around RCB stars is of great interest. An old PN that is no longer ionized could still be seen around a cool RCB star in starlight reflected from dust. An example of such a reflection nebula is the nebulosity observed around UW Cen (Pollacco et al. 1991). This is the only cool RCB star known to have a visible nebula.[7] However, an extended shell-like structure around R CrB has been detected at 100 μm (Walker 1986).

2. OBSERVATIONS

The light curve of UW Cen has been provided by the American Association of Variable Star Observers (AAVSO; J. Mattei 1999, private communication). The two observational epochs discussed here occurred during very deep declines of UW Cen when the star was ~6 mag below maximum ($V_{\rm max} \sim 9.5$). The left panel of Figure 1 shows the V-band image of UW Cen obtained on 1990 May 16/17 with the ESO New Technology Telescope when the star was at $V = 16.5$. The description of

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[7] V348 Sgr, a hot RCB star, has an ionized nebula surrounding it (Pollacco, Tadhunter, & Hill 1990).

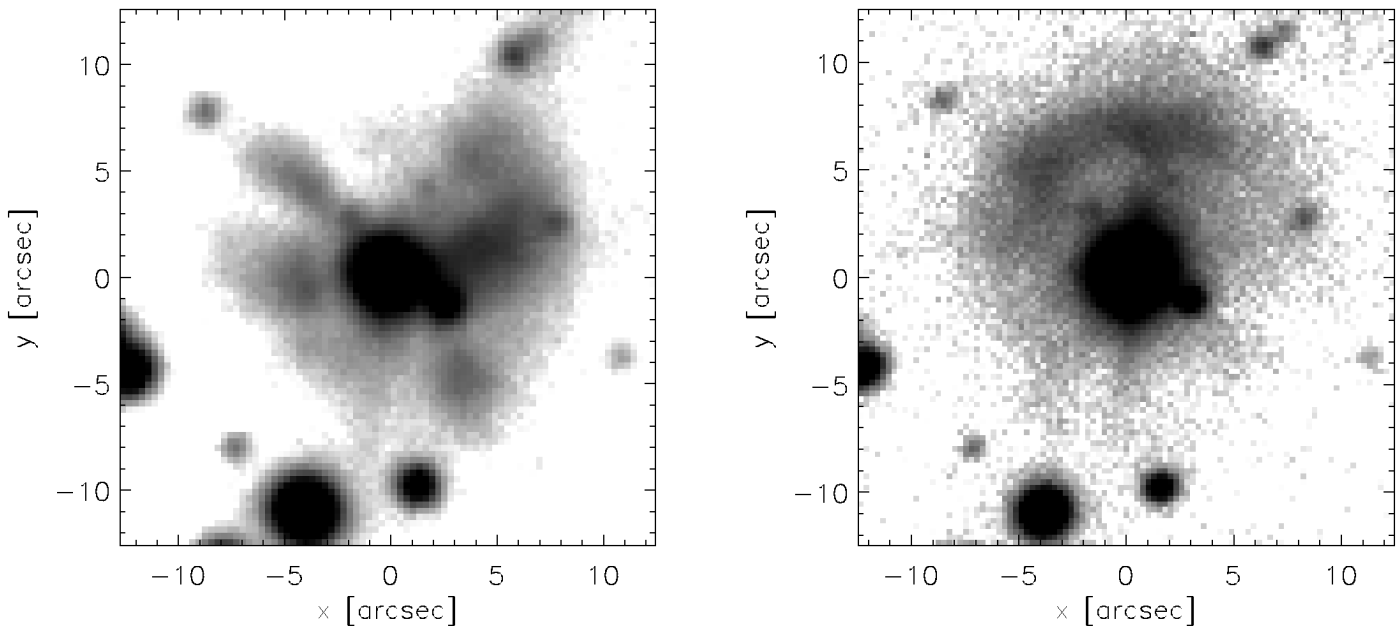

FIG. 1.—*Left*: UW Cen nebula in 1990 (Pollacco et al. 1991). *Right*: UW Cen Nebula in 1998. Both images are plotted as log flux. The nebulosity ranges from 20.7 to 23.9 mag arcsec^{-2}. The axes are right ascension offset (x) and declination offset (y). The sources that appear in this figure but not in Fig. 2 are field stars.

instrument setup and reduction is contained in Pollacco et al. (1991). The image scale is 0.″3 pixel^{-1}, and the seeing was ~1″. We have obtained new *BVR*-band images and low-resolution spectra using the 1 and 2.5 m telescopes at Las Campanas Observatory. At the 1 m Swope telescope, we used the SITE No. 1 chip (2048 × 2048 pixels) that gave a field of view of almost 24′ at a scale of 0.″69 pixel^{-1}. At the 2.5 m du Pont telescope, we employed the TEK 5 chip (2048 × 2048 pixels) with 24 μm pixels resulting in a scale of 0.″26 pixel^{-1}. In all observations, two or three exposures of 100–600 s duration, depending on the filter used, were taken and co-added during reduction. The intensities in the 1 m telescope images were calibrated using observations of the PG 1323−086 field that were obtained before and after the UW Cen images (Landolt 1992). The 2.5 m images were then calibrated using the 1 m data. Only the *V*-band image from the 2.5 m telescope is shown in the left panel of Figure 1. It was obtained on 1998 February 12 when UW Cen was at $V = 14.4$ and the seeing was better than 1″.

3. MODELING THE NEBULA

Figure 1 shows how different the UW Cen nebula appears in images taken just 8 years apart. In 1990, the nebulosity is seen predominantly to the west of the star, with clumps to the northeast, east, and southwest. In 1998, there is shell-like nebulosity covering about 45° to the north of the star and very little elsewhere. The nebula has a diameter of approximately 15″ centered on the star. The best estimate of the distance to UW Cen is 5.5 kpc (Lawson et al. 1990). The physical radius of the nebulosity is then about 6×10^{17} cm or 0.6 lt-yr. In order for material to flow from the star to the edge of the visible nebula in only 8 years, an outflow velocity of ~24,000 km s^{-1} would be necessary. Such a large velocity has never been seen in an RCB star. Outflow velocities of a few hundred kilometers per second are typically seen in the circumstellar gas during declines (Clayton 1996). If this is a final flash shell, then 30–40 km s^{-1} is a more reasonable velocity (Guerrero & Manchado 1996). Therefore, the apparent changes seen between 1990 and 1998 were not caused by an actual change in the distribution of dust clouds in the nebula. The likely explanation is that the dust nebula around UW Cen is being illuminated through shifting holes in a changing distribution of newly formed dust near the star (Feast 1996). Since both images were obtained during deep declines, we can surmise that dust had recently formed around UW Cen in both instances. To investigate this idea, we have produced a simple model of UW Cen and its circumstellar dust.

We employed the DIRTY radiative transfer model (Gordon, Witt, & Clayton 1999). This model uses Monte Carlo techniques to calculate the radiative transfer through arbitrary distributions of dust viewed from any angle. The inputs to DIRTY are the stellar distribution, in this case one star, the dust distribution, and the dust grain properties. We have modeled the dust distribution in the UW Cen nebula using two concentric shells. The model inner shell lies near the star and represents the new dust clouds that form during a decline episode. This shell is optically thick, $\tau_V = 3$, but contains a number of holes through which starlight shines, illuminating the outer shell. The model outer shell is a 1″ thick homogeneous shell of dust located at a distance of 6.″5–7.″5 from the star. In between the two shells, there is a uniform distribution of dust having a density that is a factor of 10 below that of the outer shell. The optical depth of the nebula, not including the inner optically thick shell, is small, $\tau_V = 0.19$. The dust albedo and scattering phase function are computed assuming amorphous carbon grains similar to those deduced for V348 Sgr (Hecht et al. 1998). The size distribution of the dust grains is a modified gamma function over the interval of 0.03–0.10 μm. The resulting dust albedo in the *V* band is 0.025, and the Henyey-Greenstein scattering phase function asymmetry is 0.14. Very good fits to the two images were produced by varying the number, size, and optical depth of the holes in the inner shell.

Our model images are shown in Figure 2. Only a few holes in the inner shell are necessary to fit the observed nebula. The

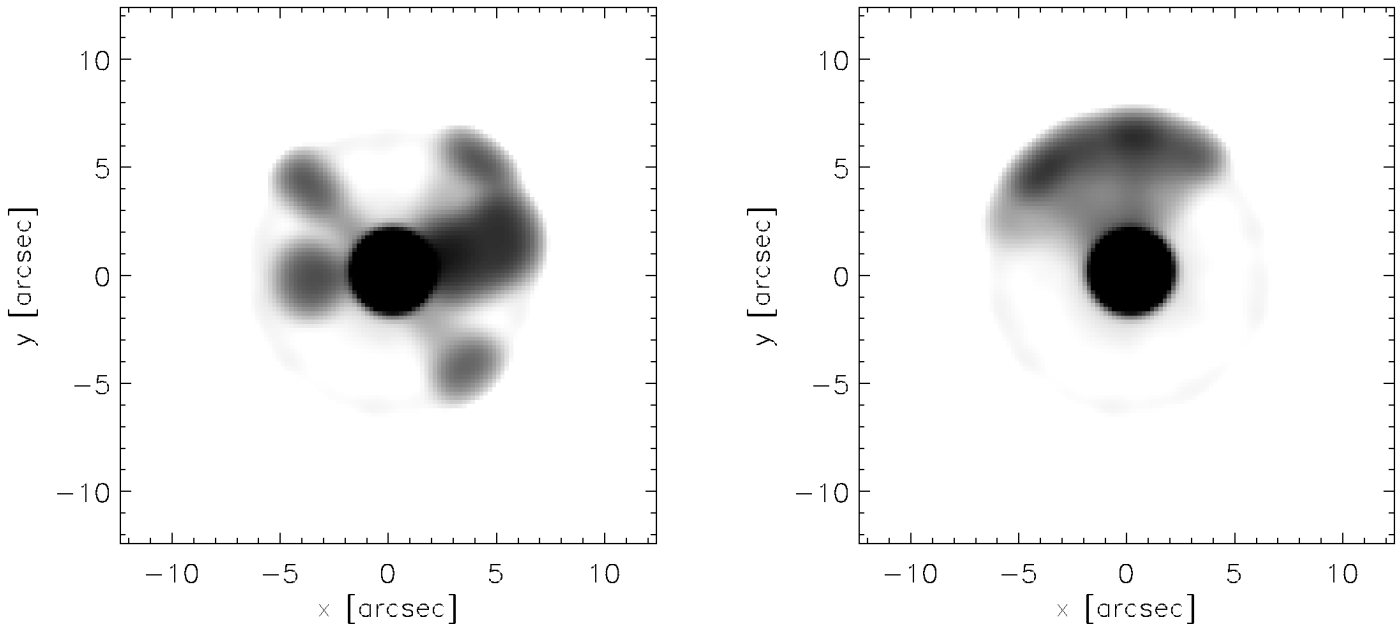

FIG. 2.—Monte Carlo dust scattering models: the UW Cen nebula in 1990 (*left*) and the UW Cen Nebula in 1998 (*right*). They are plotted as described in Fig. 1.

covering factors of the inner shell in these models are 87% and 89% for the 1990 and 1998 images, respectively. These numbers include a 5% contribution from photons passing through the $\tau_V = 3$ inner shell. However, the covering factor of the hemisphere facing away from the line of sight is not strongly constrained in this model. It is possible to uncover a significant proportion of the back of the star, ~20% of the surface area of the whole star, without seeing significant variation in the model images. The dust behind the star contributes less to the scattered light because of the slight asymmetry in the scattering phase function. The model used here was chosen for simplicity. It is not unique. The observations could also be modeled using a clumpy outer shell and a smaller covering factor for the star. A more complete picture of the actual appearance of the UW Cen nebula can be seen in the sum of the 1990 and 1998 images, which indicates that the actual nebula may be a fairly symmetric shell centered on the star. However, with only two images, there is no way to tell whether the missing portions of the outer nebula are eclipsed in both declines or whether the outer nebula is not a complete shell. When its true morphology is determined, the UW Cen nebula can be compared with the final flash stars. In A30, for example, the PN is symmetric while its final flash shell is very clumpy (Guerrero & Manchado 1996). More images obtained during declines of UW Cen are needed to map the nebula more fully.

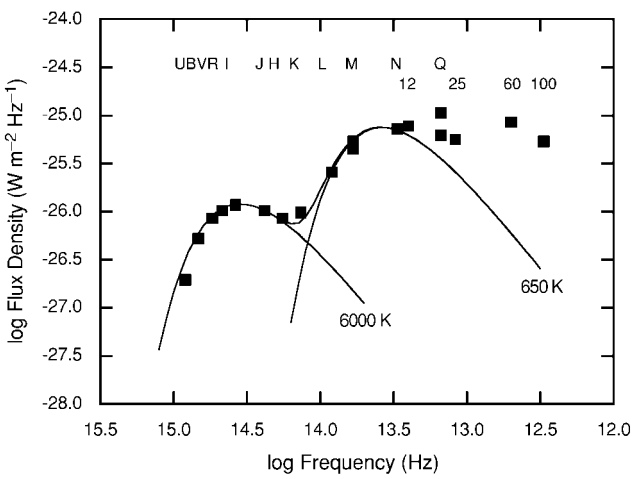

FIG. 3.—Flux distribution of UW Cen

4. DISCUSSION

The UW Cen nebula is very tenuous. The maximum surface brightness is ~21–22 mag arcsec^{-2}. Our model implies that the total optical depth from the star through the visible nebula is ~0.2. The $B-V$ colors of the UW Cen nebula are typical of those observed for other reflection nebulae. Also, the spectrum of the nebulosity in 1998 clearly shows an RCB star spectrum, indicating that it is light reflected from the star. The 1990 spectrum of the nebula is featureless (Pollacco et al. 1991). Assuming the amorphous carbon grains used for our model, the dust mass is $\sim 6 \times 10^{-4}\ M_\odot$. If we assume a normal gas-to-dust ratio and hydrogen abundance for the nebula, then the total mass is $\sim 0.2\ M_\odot$. UW Cen is extremely hydrogen deficient, and nothing is known about the abundances in the nebula, so this estimate in very uncertain. The mass of the final flash shell of A30 has been estimated to be $\sim 0.1\ M_\odot$. The large *IRAS* shell around R CrB has an estimated mass of $\sim 0.3\ M_\odot$ (Gillett et al. 1986).

Comparisons of the direct emission and reradiation from circumstellar dust in the IR give clues to the covering factor of new dust clouds forming around RCB stars (Clayton 1996 and references therein). Figure 3 shows the flux distribution for UW Cen. The photometry of UW Cen was obtained from Jones et al. (1989), Kilkenny & Whittet (1984), and the *IRAS* Point Source Catalog. The optical and near-IR photometry was obtained when the star was at, or near, maximum light. These fluxes were dereddened assuming a small optical extinction ($A_V \approx 0.2$ mag; Lawson et al. 1990) and using the typical diffuse

interstellar extinction law (Rieke & Lebofsky 1985; Cardelli, Clayton, & Mathis 1989).

The stellar (optical and near-IR) flux and dust nebula flux (mid- and near-IR wavelengths) were fitted by two Planck functions with temperatures of 6000 ± 500 and 650 ± 50 K, respectively. Planck functions tend to underestimate the $T_{\rm eff}$ of the star by 500–1000 K. UW Cen is an F-type RCB star like R CrB and RY Sgr, which has $T_{\rm eff}$ of 7000 ± 500 K (Lawson et al. 1990). Wavelengths longer than 12 μm probably show the effect of bright IR cirrus toward UW Cen. The cirrus contribution can be fitted with a 100 K Planck function. The luminosity ratio $F_{\rm IR}/F_\star$ was calculated for UW Cen, where $F_{\rm IR}$ is the integrated flux of the Planck fit to the IR excess and $F_\star$ is that for the star. For UW Cen, we derive a ratio of $F_{\rm IR}/F_\star \sim 0.3$. This is comparable to values given for UW Cen and other RCB stars based on long-term IR photometry (Feast et al. 1997). They find an apparent upper limit of $F_{\rm IR}/F_\star \sim 0.5$ for RCB stars. So, typically, no more than 50% of the stellar radiation is absorbed by the circumstellar clouds and reradiated in the IR. This value does not depend on whether the RCB star is at maximum or in decline. Typically, no significant change is measured in the IR flux during an RCB decline, indicating that the covering factor does not increase by a large amount.

Several studies of UV extinction due to the RCB circumstellar dust have estimated the covering factor (f) of the dust clouds by fitting the extinction and scattering in the dust. For the cool RCB stars, R CrB and RY Sgr, Hecht et al. (1984) find $f \lesssim 0.5$. These estimates are consistent with the visible/IR result and imply an upper limit of $f = 0.5$ for RCB stars. However, the results of our modeling of the UW Cen nebula imply a very high covering factor. This result is softened by the fact that the model is somewhat insensitive to the value of f on the far side of the star and that there are only data from two declines. The covering factor undoubtedly varies from decline to decline.

As mentioned above, the visible nebula of UW Cen may be evidence of a final flash event in the past. Six PNs in the Galaxy, A30, A78, Sakurai's object, FG Sge, IRAS 18333−2357, and IRAS 15154−5258, are hydrogen deficient and are thought to be examples of final flash objects (see, e.g., Guerrero & Manchado 1996; Jacoby, De Marco, & Sawyer 1998; Gonzalez et al. 1998). Each of these objects has a PN surrounding a smaller final flash shell. For UW Cen, we would expect dust traveling at 35 km s^{-1} to have a diameter of ~16″ after 6000 yr. Predicted timescales indicate that the final flash will happen ~9000–18,000 yr after the first ejection, depending on mass (Blöcker 1995; Iben et al. 1983), and that the star will rejoin the asymptotic giant branch (AGB) a few hundred years after the final flash. If the star becomes an RCB shortly afterward (as indicated by Sakurai's object) and stays that way for ~3000–10,000 yr (Iben et al. 1996), then we would expect the PN for UW Cen to have a diameter of 24″–50″, the final flash shell to have a diameter of 8″–26″, and RCB dust within the other two shells. This agrees well with the measured value of 15″ for the UW Cen nebula. Since only one nebula has been detected around UW Cen, it could be either an old PN or the final flash shell. The apparent symmetry of the visible nebula around UW Cen would be consistent with many PNs. Alternatively, the nebula could be a windblown bubble in the interstellar medium. At 20 km s^{-1}, windblown dust could form the observed nebula in 9500 yr. A link between RCB stars and PNs, if it can be established, will be an important step forward in understanding the evolution of post-AGB stars. More observations are necessary both to map out the nebula of UW Cen and to resolve the disagreement between the large dust covering factor predicted by the model and the smaller values inferred from UV and IR data.

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