The Astrophysical Journal, 660:341 – 345, 2007 May 1

MULTIPLE COAXIAL RINGS IN THE BIPOLAR NEBULA HUBBLE 12

Sun Kwok[1] and Chih Hao Hsia[2,3]
Received 2006 October 30; accepted 2007 January 18

ABSTRACT

A series of two-dimensional rings along a common axis aligned with the bipolar lobes is found in the planetary nebula Hb 12. The rings have separations of about 0.3″, which can be translated into physical separations of ∼1000 AU, or time separations of the order of 50 yr. We suggest that the existence of the rings is a manifestation of the interaction between a time-variable, collimated fast outflow with the circumstellar envelope created by the stellar wind of an asymptotic giant branch star. Comparison of Hb 12 with other bipolar nebulae with hourglass structures such as Hen 2-104, MyCn 18, and SN 1987A suggests that the nebula of Hb 12 may represent the inner nebula of a much larger bipolar structures, and we propose to search for such outer structures with a wide-field infrared camera.

Subject headings: binaries: symbiotic — planetary nebulae: general — planetary nebulae: individual (Hubble 12) — stars: AGB and post-AGB

1. INTRODUCTION

Since its discovery by E. Hubble in 1921 (Hubble 1921), Hb 12 has mystified astronomers for its unusual properties. Hb 12 is classified as a planetary nebula (PNG 111.8-02.8) by its emission-line spectrum, although its optical nebulosity was not spatially resolved until recently. Even by the standard of stellar planetary nebulae, Hb 12 has a very high surface brightness, among the highest of all known planetary nebulae. It is bright in the infrared (21 Jy at 12 μm according to *IRAS* Point Source Catalogue) and in the radio (45 mJy at λ6 cm; Aaquist & Kwok 1990). Most interestingly, it has a rising radio spectrum with a spectral index of ∼1.2 and a very high turnover frequency of 28 GHz (Purton et al. 1982; Aaquist & Kwok 1991). A model fit to its spectral energy distribution suggests that 55% of its total flux is emitted in the dust component of temperature ∼200 K (Zhang & Kwok 1991). All these properties point to the fact that it is a planetary nebula at a very early age of development.

Ground-based near-IR H_2 image of Hb 12 reveals an eye-shaped structure, which can be identified as the equatorial torus of a bipolar nebula (Hora & Latter 1996). Such a bipolar structure is confirmed by later *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 (WFPC2; Sahai & Trauger 1998) and Near-Infrared Camera and Multi-Object Spectrometer (NICMOS; Hora et al. 2000) observations. The observed morphology of Hb 12 is similar to that of MyCn 18 (Sahai et al. 1999) and Hen 2-104 (Corradi et al. 2001). Hora & Latter (1996) call Hb 12 "a butterfly in the making" and as such is an important object to study the morphological transformation to bipolar morphology in post–asymptotic giant branch (post-AGB) evolution.

2. OBSERVATION

High-resolution optical images form Hb 12 using the WFPC2 on *HST* through the observation program 9050 (PI: B. Balick) in Cycle 10. The object was observed with the Planetary Camera (PC), which provides an 36.8″ × 36.8″ field of view at a 0.046″ pixel^{-1} scale. The observation was made with narrowband filters F502N [O III], F656N (Hα), and F658N [N II]. Images of Hb 12, based on these observations, were published by Balick (2003). Images based on earlier observations with the F656N and F487N filters were published by Sahai & Trauger (1998).

After examining the data from the *HST* archive, we found that the F658N filter (λ_p = 6591 Å, $\triangle\lambda$ = 29 Å) observations contain previously unrevealed structures of the nebula. We have produced an image using the combined F658N observations with a total exposure time of 1300 s. Data were taken in two-step dithered positions to enhance spatial sampling and by using the IRAF/STSDAS task `crrej` to remove cosmic rays. Standard flat-fielding and bias subtraction were performed. Individual frames were then combined using the `drizzle` task in IRAF/STSDAS.

The reduced [N II] image of Hb 12 is shown in Figure 1. A pair of bipolar lobes of an hourglass shape is clearly visible. After the application of an image-enhancement method, "unsharp mask," the contrast between the lobe structure and sky emission was improved by a factor of $\gtrsim$2. A set of rings can be seen along the bipolar lobes.

In addition to the WFPC image, we have also retrieved the NICMOS F160W image of Hb 12 from the *HST* archive (program 7365; PI: W. B. Latter). The NICMOS image, after the application of the unsharp mask, is shown in Figure 2.

3. RESULTS

The high quality of the [N II] image offers us the opportunity to derive accurate parameters of the structure of the nebula. The bipolar axis lies approximately along the north-south direction, and the axis of the bipolar lobes is measured to have a position angle of 171.5° ± 2.3°. An earlier estimate by Miranda & Solf (1989) has placed the position angle as 0°. A series of nine ellipses (five in the northern lobe and four in the southern lobe) is fitted by eye to the two-dimensional rings. These ellipses are consistent with a series of tilted concentric circles with a common axis. The position angle of the major axis of the rings is measured to be 88° ± 1.5°. The sizes of the ellipses are 4.93″ × 3.03″, 4.43″ × 2.73″, 4.03″ × 2.48″, 3.68″ × 2.26″, and 3.08″ × 1.90″ for the rings *a*, *b*, *c*, *d*, *e* of the northern lobes, respectively. For the southern lobe, the sizes of the ellipses are 3.26″ × 2.01″,

[1] Department of Physics, University of Hong Kong, Pokfulam Road, Hong Kong, China; sunkwok@hku.hk.
[2] Institute of Astronomy, National Central University, Chung Li 32054, Taiwan; d929001@astro.ncu.edu.tw.
[3] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China.

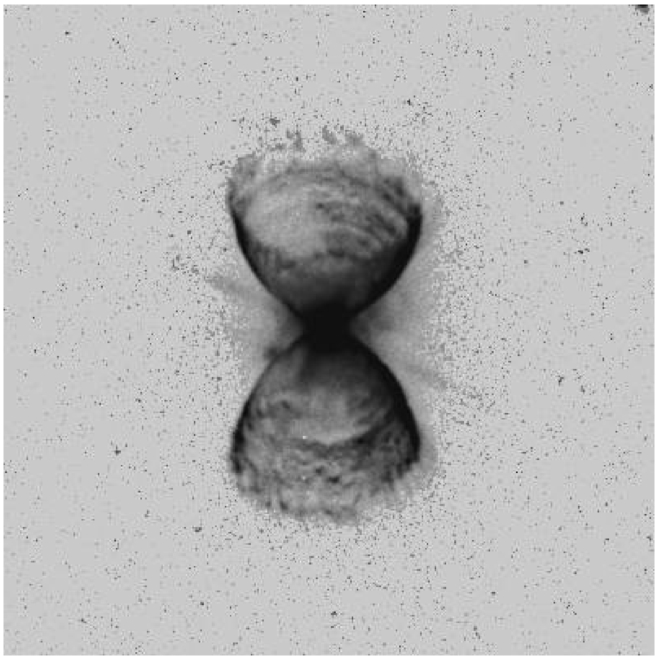

FIG. 1.—*HST* WFPC2 [N II] image of Hb 12 after the application of an unsharp mask. All images in this paper are displayed with a logarithmic gray scale.

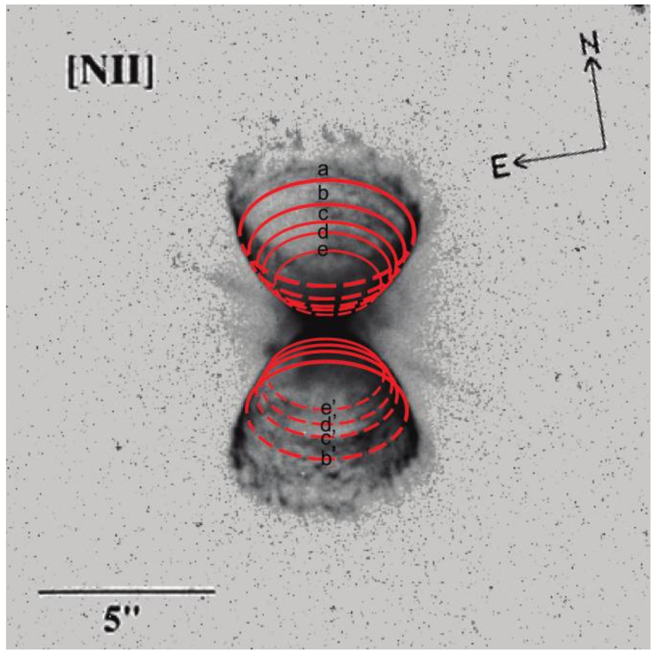

FIG. 3.—Schematic drawing illustrating the outlines of nine concentric rings in the bipolar lobes of Hb 12. Since projected circles can have two ambiguous interpretations, we have plotted the front side of the ellipses in solid lines and the back side in dotted lines.

$3.77'' \times 2.31''$, $4.07'' \times 2.51''$, and $4.58'' \times 2.82''$ for the rings e', d', c', b', respectively (Fig. 3). Based on these measurements and visual inspection, we could consider the rings b', c', d', and e' to be the counterparts of b, c, d, and e. Assuming that these ellipses are tilted circles, the angles of tilt (i) of the five rings are all approximately 38° (with 0° being edge-on). This inclination angle is consistent with the value of 40° derived for the lobes by Hyung & Aller (1996), with the southern lobe tilted toward the observer. For comparison, an inclination of 30° was found for the equatorial torus (Hora & Latter 1996). Although the northern lobe appears brighter than the southern lobe in the *HST* image, recent kinematic studies have shown that the southern lobe is in fact in front (A. López 2006, private communication).

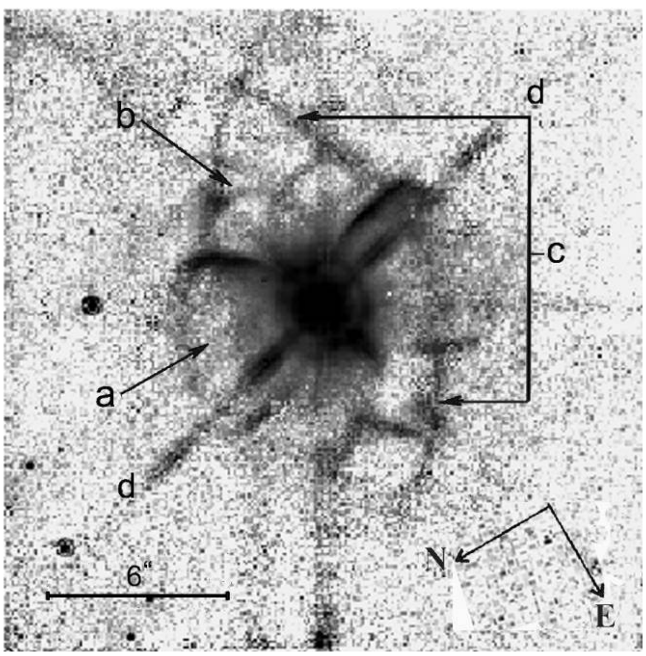

FIG. 2.—*HST* NICMOS image of Hb 12 after the application of an unsharp mask. Exposure time for this image is 256 s. The primary bipolar lobes, the rims of the inner "hourglass," and the equatorial ring are marked by *a*, *b*, and *c*, respectively. A long linear jet (marked as *d*) can be seen emanating from the central star along the bipolar axis of the lobes.

The interring separations (θ) are measured to be $0.46''$ (a–b), $0.35''$ (b–c), $0.21''$ (c–d), and $0.31''$ (d–e). Correcting for the 38° projection, the actual distance between the rings along the bipolar axis can be written as

$$\Delta = 1.9 \times 10^{16} \left[\frac{(\theta/\mathrm{arcsec})(D/\mathrm{kpc})}{\cos(i/38°)} \right] \mathrm{cm}$$
$$= 1269 \left[\frac{(\theta/\mathrm{arcsec})(D/\mathrm{kpc})}{\cos(i/38°)} \right] \mathrm{AU}, \qquad (1)$$

where D is the distance to Hb 12. The estimates of distances to Hb 12 vary widely. They range from 2.24 kpc (Cahn et al. 1992) to 8.1 kpc (Zhang 1995). If we assume $D = 3$ kpc and $\theta = 0.3''$, the physical separation is $\sim 1.7 \times 10^{16}$ cm, or 1140 AU, or 0.02 lt-yr. For an expansion velocity of $V = 100$ km s^{-1}, the above value translates into a time interval between rings of $\Delta/V \sim 54$ yr.

In the NICMOS image (Fig. 2), the bipolar lobes of Hb 12 can be seen, although not to the degree of detail seen in the WFPC image. However, the equatorial features are shown much better in the NICMOS image. The outlining structure of the "eye" (Hora & Latter 1996) can be considered as the rim of an equatorial ring. A pair of inner "hourglasses," with an opening angle larger than the main bipolar nebula, can also be discerned. Most interestingly, an extended, highly collimated, linear jetlike feature can been seen along the axis of the bipolar nebula. This feature is not seen in the WFPC2 image and is highly unusual in bipolar planetary nebulae. This suggests that highly collimated outflows take on many forms, with a wide range of degree of collimation. There

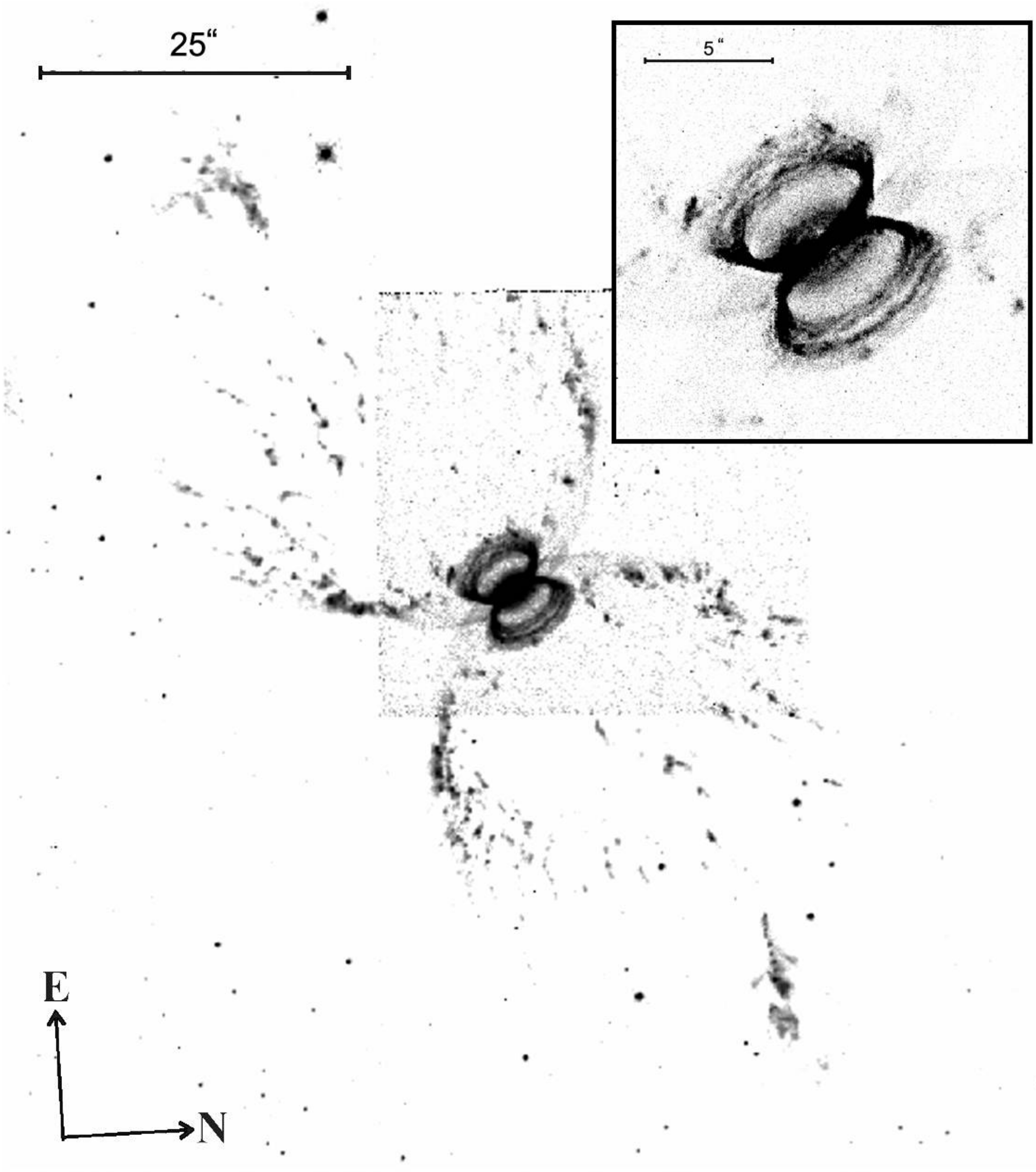

Fig. 4.—*HST* WFPC2 [N ii] image of Hen 2-104 after the application of an unsharp mask. Data from *HST* data archive, program 7379 and 9336 (PI: R. L. M. Corradi). The image is made from the combination of two data sets with a total exposure time of 4000 s + 3760 s.

are at least three different kinds in Hb 12, counting the inner and outer hourglasses and this jet.

4. DISCUSSION

The structure of Hb 12 (bipolar lobes with multiple rings) closely resembles the inner regions of SN 1987A (Panagia et al. 1996; Sugerman et al. 2005) and Hen 2-104 (Corradi et al. 2001). Similar structures can also be found in the planetary nebula MyCn 18 (Sahai et al. 1999) and He 2-113 (Sahai et al. 2000). The basic structure can be described as an hourglass with a tight waist and open rims. In the case of the inner hourglass of Hen 2-104, there are three rings on each side of the lobes (Corradi et al. 2001). Similarly, there is a pair of rings in the inner hourglass of MyCn 18 (Sahai et al. 1999). We have reproduced the unsharped [N ii] images of Hen 2-104 and MyCn 18 in Figures 4 and 5.

Since the shape of the hourglass is well defined, it suggests that the nebula is confined by pressure from an unseen external medium, probably a dense equatorial dust torus or a spherical envelope. The waist of the hourglass, when projected onto the sky at an angle, takes on the appearance of an "eye," as in the cases of SN 1987A, Hb 12, and MyCn 18. The rings define the rims of the hourglass. In order to confine the nebula boundaries so well, this external medium must be very large. It is likely that this medium is where the $\sim$200 K dust component emission originates, although this has to be confirmed by future far-infrared imaging. This suggests that the optical nebula of Hb 12 is likely to only represent a small fraction of the total circumstellar mass. If we take the analogy to Hen 2-104 and SN 1997A further and assume that the observed nebula of Hb 12 only represents the inner region of a much larger bipolar nebula, then the total extent of the object is also much bigger. A deep exposure with the [N ii] filter or in molecular hydrogen should be able to reveal such large structures.

It is also interesting to note that near the outer rim of the south lobe, a series of linear "jetlike" features can be seen emanating

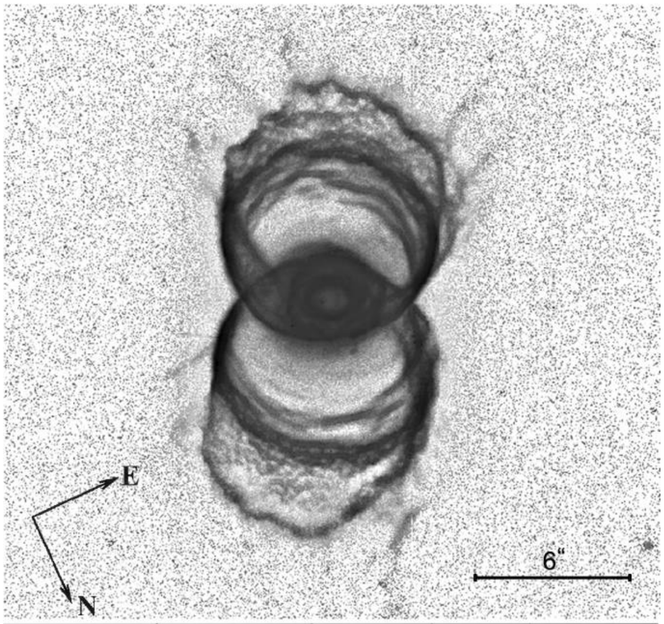

FIG. 5.—*HST* WFPC2 [N II] image of MyCn 18 after the application of an unsharp mask. Data from *HST* data archive, program 6221 (PI: J. T. Trauger). The total exposure time is 700 s.

from the surface of the lobe, resembling the structures seen in NGC 6543, Mz 3 (Guerrero et al. 2004), and MyCn 18 (Fig. 5). These features are linear, highly collimated, and probably fast moving. The morphology of these features suggests that they represent a breakout of very fast outflows from an existing medium.

If the outline of the Hb 12 nebula (hourglass) is defined by an ionization front, then the nebula probably was carved out by a collimated fast wind along the polar directions from the surrounding circumstellar medium. If this fast outflow is not steady, or if it is episodic and comes in "puffs," then successive rings (rims of the hourglass) can be created. From the time separations estimated in § 3, the time interval between puffs is of the order of 50 yr. What kinds of physical mechanisms can lead to episodic ejections of such intervals? One possibility is that the outflow is modulated by a binary system of central stars. For example, Soker (2005) suggests that the "spider web" structure (possibly edge-on rings) of HD 44179 is formed by intermittent jets blown by an accreting binary central system. In our reprocessed [N II] image of M2-9 (Fig. 6), some edge-on rings can also be seen.

If the rings are the consequence of binarity, then Hb 12 and M2-9 may be more related to the symbiotic phenomenon in the class of objects such as V1016 Cyg and HM Sge than planetary nebulae (Kwok 2003). This possibility was discussed by Corradi (2003), who lists Hb 12, Hen 2-104, and M2-9 as three of the nine planetary nebulae that could be symbiotic stars. The fact that the central stars of Hb 12 are an eclipsing system (Hsia et al. 2006) adds further credibility to this hypothesis. If Hb 12 is indeed a symbiotic system, then the external circumstellar medium is probably created by a stellar wind from the AGB component, and the collimated fast outflow originates from an hydrogen-shell burning white dwarf companion.

Due to the enhanced brightness of the rings compared to the rest of the nebula, they probably represent regions of higher density. The morphology of the rings is clearly two-dimensional, which makes them different from the phenomenon of concentric arcs, which are projections of spherical shells on the plane of the sky (Sahai et al. 1998; Kwok et al. 2001). Since the term "ring" has also been used in the literature to refer to the arcs, we want to make a specific and clear distinction between the two phenomena and use different terms to refer to them. The concentric arcs

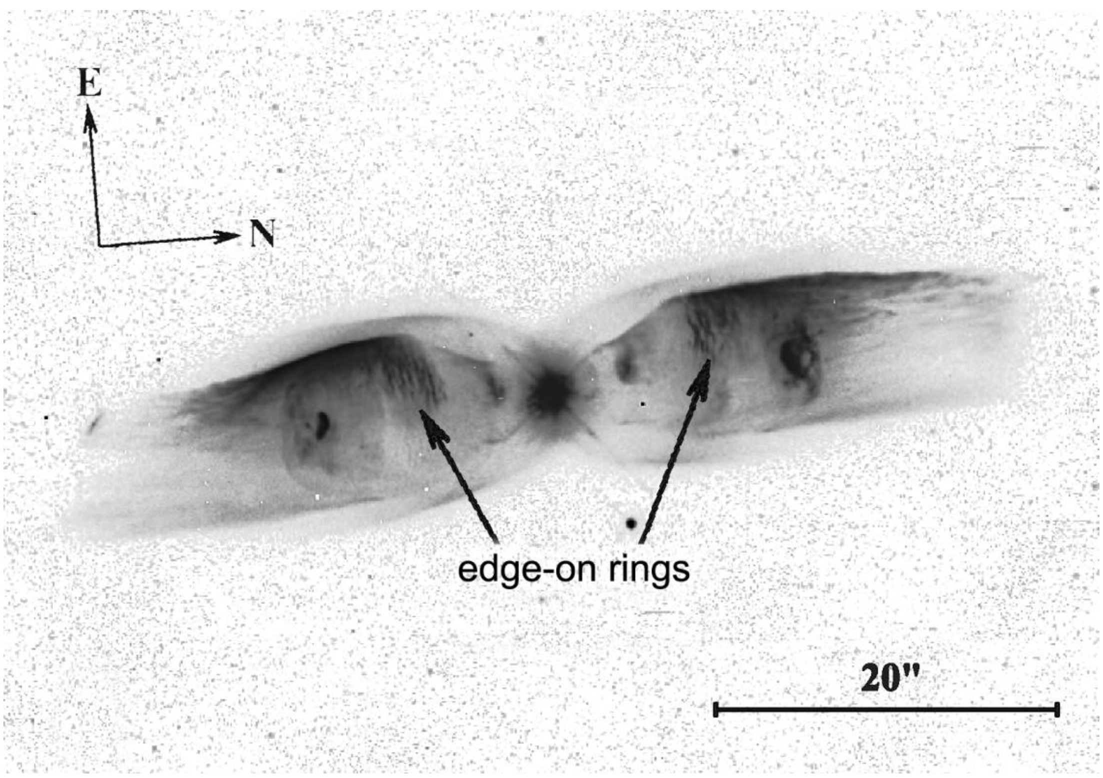

FIG. 6.—*HST* WFPC2 [N II] image of M2-9 after the application of an unsharp mask. Data from *HST* data archive programs 6502 (PI: B. Balick) and 8773 (PI: A. R. Hajian). The total exposure time is 1240 s + 1300 s.

generally have larger time separations (of the order of several hundred years) and are believed to be manifestations of the periodic nature of the mass-loss phenomenon on the AGB. This is different from the rings, as they are, we believe, caused by the periodic nature of the fast wind. Evidence for the episodic fast wind in Hb 12 can be found in the structure of the [Fe II] emission (Welch et al. 1999). An alternative scenario would be that the fast wind is continuous, and the rings are caused by its interaction with the discrete shells formed by the periodic AGB wind. However, the latter interpretation is only possible if the inter-arcs' and inter-rings' time separations are indeed the same.

On a larger scale, the origin of the multiple hourglasses is also unknown. The existence of coaxial inner and outer hourglasses with different opening angles in SN 1987A, Hb 12, Hen 2-104, etc., suggests that they represent successive dynamical events. If they are indeed the result of time-variable outflows, then the multiple rings on the surface of each of the hourglasses represent dynamical events on a shorter timescale. Since a binary central-star system has many more possibilities of generating events on different timescales (e.g., orbital motion, accretion episodes, etc.), the observed structures would be easier to explain under a binary scenario.

However, spectroscopic studies of the multiple hourglasses in Hen 2-104 suggest that the outer hourglass (in terms of distance from the central star, not in opening angle) is expanding faster than the inner hourglass (Corradi et al. 2001). In fact, the kinematic ages are similar for both, implying a simultaneous ejection. A similar Hubble flow situation has also been suggested for the different outflow components of Mz 3 (Santander-Garcá et al. 2004). If this is the case, the multiple hourglasses would most likely be the consequence of onset of thermal nuclear runaway, when mass transfer has accumulated enough hydrogen on the surface of the white dwarf for ignition. Such "nova-like" ejections are directional, with different opening angles and speeds, therefore creating multiple hourglasses. It would be interesting to do a spectroscopic observation of Hb 12 to determine the kinematic ages of the hourglasses in Hb 12.

5. CONCLUSIONS

While the interacting stellar winds model has been very successful in explaining the global structures of planetary nebulae, the discovery of arcs and rings in the nebulae has led to the realization that either or both of the AGB and later-developed fast wind could have temporal variations. This couples with the directional (collimated) nature of the fast wind, leading to interesting dynamical consequences in the nebular evolution. The results reported here exemplify what the very high angular resolution and dynamic range observations by the *HST* can do to advance these studies.

The existence of multiple rings and the measurements of the interring separations have made possible the estimation of the timescale of wind variations. These measurements are critical for the identification of the physical causes of the variations. These results have implications beyond planetary nebulae, as similar structures are seen in symbiotic stars and supernova ejecta.

This work was partially supported by the University of Hong Kong and the Natural Sciences and Engineering Research Council of Canada and by the National Science Council of Taiwan under programs NSC 94-2752-M-008-001-PAE and NSC 94-2112-M-008-002.

REFERENCES

Aaquist, O. B., & Kwok, S. 1990, A&AS, 84, 229
———. 1991, ApJ, 378, 599
Balick, B. 2003, in ASP Conf. Ser. 303, Symbiotic Stars Probing Stellar Evolution, ed. R. L. M. Corradi, J. Mikolajewski, & T. J. Mahoney (San Francisco: ASP), 407
Cahn, J. H., Kaler, J. B., & Stanghellini, L. 1992, A&AS, 94, 399
Corradi, R. L. M. 2003, in ASP Conf. Ser. 303, Symbiotic Stars Probing Stellar Evolution, ed. R. L. M. Corradi, J. Mikolajewski, & T. J. Mahoney (San Francisco: ASP), 393
Corradi, R. L. M., Livio, M., Balick, B., Munari, U., & Schwarz, H. E. 2001, ApJ, 553, 211
Guerrero, M. A., Chu, Y.-H., & Miranda, L. F. 2004, AJ, 128, 1694
Hora, J. L., & Latter, W. B. 1996, ApJ, 461, 288
Hora, J. L., Latter, W. B., Dayal, A., Bieging, J., Kelly, D. M., Tielens, A. G. G. M., & Strammell, S. R. 2000, in ASP Conf. Ser. 199, Asymmetric Planetary Nebulae II: From Origins to Microstructures, ed. J. H. Kastner, N. Soker, & S. Rappaport (San Francisco: ASP), 267
Hsia, C. H., Ip, W. H., & Li, J. Z. 2006, AJ, 131, 3040
Hubble, E. 1921, PASP, 33, 174
Hyung, S., & Aller, L. H. 1996, MNRAS, 278, 551
Kwok, S. 2003, in ASP Conf. Ser. 303, Symbiotic Stars Probing Stellar Evolution, ed. R. L. M. Corradi, J. Mikolajewski, & T. J. Mahoney (San Francisco: ASP), 428
Kwok, S., Su, K. Y. L., & Stoesz, J. A. 2001, Post-AGB Stars as a Phase of Stellar Evolution, ed. R. Szczerba & S. K. Gorny (Dordrecht: Kluwer), 115
Miranda, L. F., & Solf, J. 1989, A&A, 214, 353
Panagia, N., Scuderi, S., Gilmozzi, R., Challis, P. M., Garnavich, P. M., & Kirshner, R. P. 1996, ApJ, 459, L17
Purton, C. R., Feldman, P. A., Marsh, K. A., Allen, D. A., & Wright, A. E. 1982, MNRAS, 198, 321
Sahai, R., Hines, D. C., Kastner, J. H., Weintraub, D. A., Trauger, J. T., Rieke, M. J., Thompson, R. I., & Schneider, G. 1998, ApJ, 492, L163
Sahai, R., Nyman, L. Å, & Wootten, A. 2000, ApJ, 543, 880
Sahai, R., & Trauger, J. T. 1998, AJ, 116, 1357
Sahai, R., et al. 1999, AJ, 118, 468
Santander-García, M., Corradi, R. L. M., Balick, B., & Mampaso, A. 2004, A&A, 426, 185
Soker, N. 2005, AJ, 129, 947
Sugerman, B. E. K., Cortts, A. P. S., Kunkel, W. E., Heathcote, S. R., & Lawrence, S. S. 2005, ApJS, 159, 60
Welch, C. A., Frank, A., Pipher, J. L., Forrest, W. J., & Woodward, C. 1999, ApJ, 522, L69
Zhang, C. Y. 1995, ApJS, 98, 659
Zhang, C. Y., & Kwok, S. 1991, A&A, 250, 179