The Astrophysical Journal, 635:L49–L52, 2005 December 10

DISCOVERY OF MULTIPLE COAXIAL RINGS IN THE QUADRUPOLAR PLANETARY NEBULA NGC 6881

Sun Kwok
Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 106, Taiwan; and Department of Physics and Astronomy, University of Calgary, Calgary, AB T2N 1N4, Canada; kwok@asiaa.sinica.edu.tw

and

Kate Y. L. Su
Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; ksu@as.arizona.edu
Received 2005 March 31; accepted 2005 November 3; published 2005 November 28

ABSTRACT

We report the discovery of multiple two-dimensional rings in the quadrupolar planetary nebula NGC 6881. As many as four pairs of rings are seen in the bipolar lobes, and three rings are seen in the central torus. While the rings in the lobes have the same axis as one pair of the bipolar lobes, the inner rings are aligned with the other pair. The two pairs of bipolar lobes are likely to be carved out by two separate high-velocity outflows from the circumstellar material left over from the asymptotic giant branch (AGB) wind. The two-dimensional rings could be the results of dynamical instabilities or the consequence of a fast outflow interacting with remnants of discrete AGB circumstellar shells.

Subject headings: planetary nebulae: general — stars: AGB and post-AGB — supernovae: general

1. INTRODUCTION

Many planetary nebulae (PNs) are known to have bipolar structures. Some examples of well-known bipolar PNs are NGC 650-1, NGC 2346, NGC 6302, and Hb 5. They are characterized by two extended, butterfly-like lobes separated by a narrow waist or a dark lane. Under the general scheme of the interacting winds model of PN formation, the creation of bipolar PNs can be understood if either the slow AGB wind or the new fast wind is nonisotropic. The recent discoveries of proto–planetary nebulae (PPNs) with bipolar structures suggest that the transformation to bipolar forms occur soon after the end of the asymptotic giant branch (AGB; Kwok et al. 1996, 1998; Su et al. 1998), probably shaped by a high-velocity outflow collimated by an equatorial torus.

While this simple picture offers an excellent explanation for the bipolar PN phenomenon, modern CCD narrowband imaging surveys have revealed a new class of PNs with multiple bipolar lobes (Manchado et al. 1996). Even well-known bipolar PNs such as NGC 2440 show two or three pairs of bipolar lobes at different orientations under deep exposures (López et al. 1998). Such multipolar structures raise the possibility that the lobes are the result of episodic ejections and that precession and rotation may play a role in the history of the mass-loss process (Manchado et al. 1996; Miranda et al. 1999).

The number of known multipolar PNs has grown in recent years, largely as the result of observations with the *Hubble Space Telescope* (*HST*; Sahai & Trauger 1998; Sahai 2000). NGC 6881 (PN G74.5+0.21) is a compact (~5″) PN with a bright central core and bipolar extensions in the northwest-southeast directions (Hua et al. 1993). In the $\lambda = 6$ cm and $\lambda = 3$ cm radio images, the central core can be seen to have the structure of a torus, with faint extensions along the bipolar axis being seen in the $\lambda = 3$ cm image (Aaquist & Kwok 1990; Kwok & Aaquist 1993). Recent ground-based imaging and spectroscopic observations suggest that it could be a quadrupolar nebula with two pairs of bipolar lobes at different position angles (Guerrero & Manchado 1998). Since the *HST* offers much higher angular resolution imaging capabilities, it is ideally suited to discern the multipolar structures in compact PNs. In this Letter, we report *HST* narrowband imaging of NGC 6881 and discuss its morphological structures from these observations.

2. OBSERVATION

NGC 6881 was observed with the *HST* Wide Field Planetary Camera 2 (WFPC2) as part of the Cycle 8 program 8307 (PI: S. Kwok). Observations were made with three narrowband filters: F656N (Hα, $\lambda_p = 6564$ Å, $\Delta\lambda = 22$ Å), F658N ([N II], $\lambda_p = 6591$ Å, $\Delta\lambda = 29$ Å), and F502N ([O III], $\lambda_p = 5012$ Å, $\Delta\lambda = 27$ Å), with total combined exposure times of 280, 520, and 320 s, respectively. The object was centered on the Planetary Camera (PC) with a pixel size of 0″.046. Data were taken in two-step dithered positions to enhance spatial sampling and identify cosmic rays. None of the pixels within the nebula are saturated in the individual frames. Standard flat-fielding and bias subtraction were performed. Individual frames were then combined using the Drizzle task in IRAF/STSDAS. Finally, the images were rotated to match the canonical display: north is up, and east is toward the left. In the *HST* archive, there is also another set of observations of NGC 6881 (program 6347, PI: K. Borkowski) taken in Cycle 6. We have made use of the their [N II] observations (400 and 200 s) to make a combined image in order to improve the signal-to-noise ratio.

3. RESULTS

The final combined Hα, [O III], and [N II] images are shown in Figures 1, 2, and 3, respectively. At first glance, NGC 6881 looks like a classical bipolar nebula with an equatorial torus. In fact, there are two pairs of lobes in both [N II] and Hα images. Detailed microstructures are more prominent in the [N II] image, and a schematic sketch of the features is shown in Figure 4. All measurements of the physical sizes of the structures are derived from the [N II] image. The bipolar lobes (A, A’) are at a position angle of $148° \pm 2°$, while the lobes (B, B’) are at a position angle of $132° \pm 2°$. From kinematic data, Guerrero & Manchado (1998) suggest that the southeast inner lobe (equivalent to our lobe B’) is tilted ~15° toward us with respect to. the plane of sky. All four lobes can be roughly represented as ellipses with

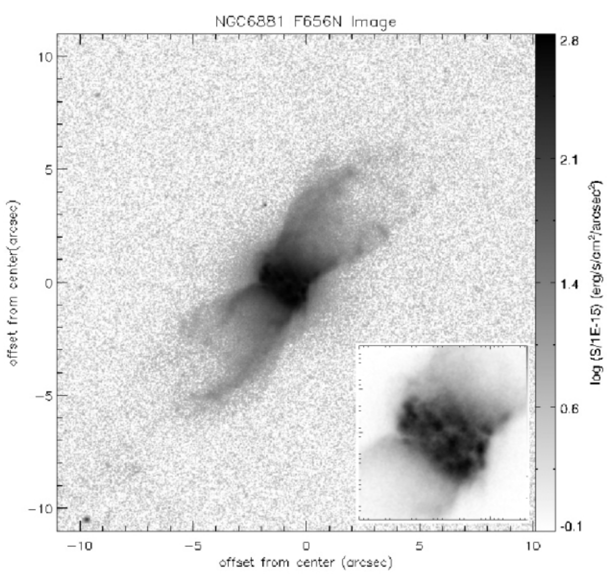

FIG. 1.—*HST* WFPC2 Hα image of NGC 6881 shown in a logarithmic scale. The panel in the lower right-hand corner displays the zoomed-in central $4'' \times 3''.8$ torus region.

major and minor axes of $8''.6 \times 3''.5$, with an error of $0''.1 \times 0''.1$ down to the 3 σ limit. These sizes just give an approximation to the main parts of the lobes and do not include the more diffuse filaments, e.g., in the northwest and southeast directions. The similar position angle and size between lobes (A, A') and (B, B') suggest that lobes (A, A') and (B, B') were formed roughly the same time by a similar physical process (e.g., a collimated bipolar jet). Therefore, lobes (A, A') and (B, B') can be considered as a point-symmetric pair.

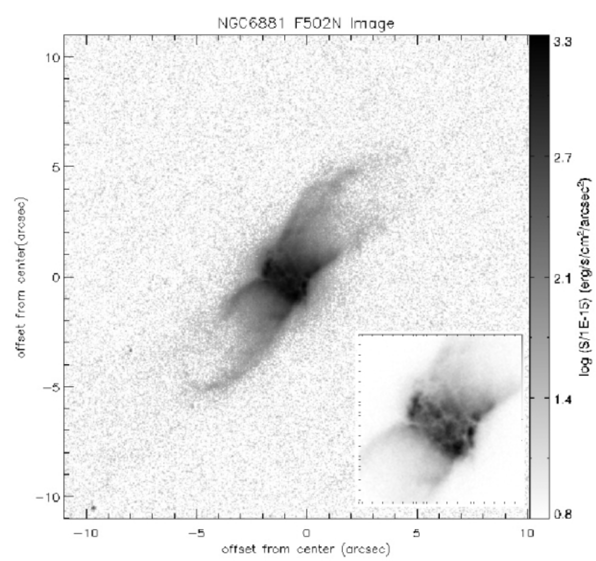

FIG. 2.—*HST* WFPC2 [O III] image of NGC 6881 shown in a logarithmic scale. The panel in the lower right-hand corner displays the zoomed-in central $4'' \times 3''.8$ torus region.

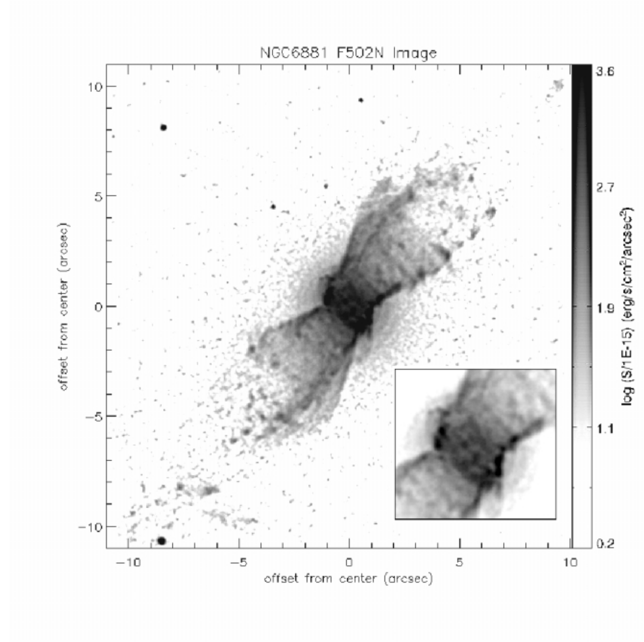

FIG. 3.—*HST* WFPC2 [N II] image of NGC 6881 shown in a logarithmic scale. The panel in the lower right-hand corner displays the zoomed-in central $4'' \times 3''.8$ torus region.

The bright central core can be seen to resolve into several bright clumps in a torus-like structure. This core is estimated to have a size of $2''.9 \times 1''.7$ (major axis times minor axis) at a position angle of $47° \pm 2°$ down to the 10 σ limit. This is consistent with the radio image, where the two bright spots represent the longer column densities seen along edges of an edge-on torus (Aaquist & Kwok 1990; Kwok & Aaquist 1993).

The bipolar lobes have well-defined boundaries and appear to be open-ended rather than closed bubbles. The morphology of the lobes suggests that they are confined by an external

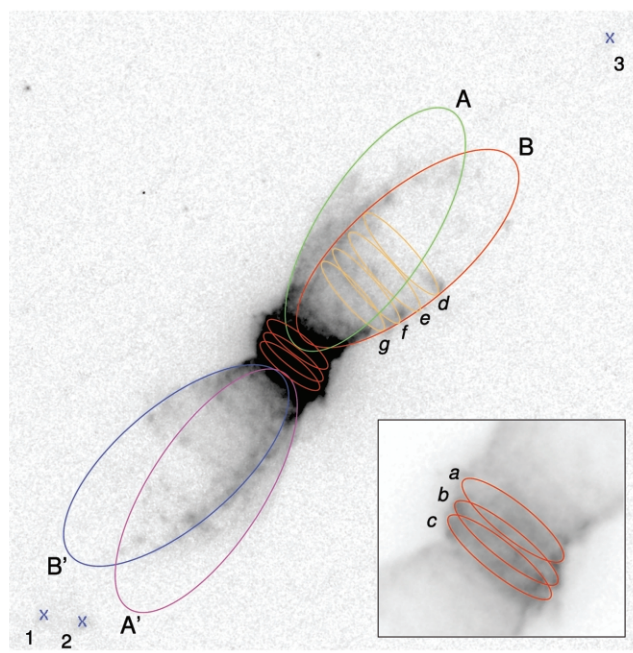

FIG. 4.—Schematic drawing illustrating the outlines of the two pairs of bipolar lobes. Some of the rings and knots discussed in the text are also labeled.

medium, possibly cold, neutral gas ejected during the previous AGB phase. The bipolar lobes represent regions carved out by the post-AGB fast outflow and photoionized by the central star.

Although not obvious in the Hα and [O III] images, several rings can be clearly seen both in the torus and in the lobes in the [N II] image (Fig. 4). There are three central rings (labeled as *a*, *b*, and *c*) that can be identified in the central torus along the position angle of ∼52°. These central rings have an approximate size (major axis times minor axis) of 2″.3 × 0″.6 and an interring separation of ∼0″.4. Assuming that these rings are circular, their projected images suggest an orientation of ∼75° (90° being edge-on). No pointlike source (the central star of the PN) is detected in any of the three images.

Four rings (labeled as *d*, *e*, *f*, and *g*) can be easily identified in lobe B, and lobe B' also shows similar traces of the counterparts of these four rings in the opposite direction. Rings *d*–*g* have position angles of ∼43°, which are perpendicular to the major axis of lobe B. The approximate sizes (major axis times minor axis) of these four rings are 3″.4 × 0″.8, 3″.3 × 0″.7, 2″.8 × 0″.6, 3″.1 × 0″.6, for the rings *d*, *e*, *f*, and *g*, respectively. The interring separations are 0″.5 (*d*–*e*), 0″.7 (*e*–*f*), and 0″.7 (*f*–*g*). Similar to the central rings, the projected images suggest an orientation of ∼77°, assuming the rings are circular. Assuming that the separation of the rings is due to episodic fast winds (§ 4), the observed separation implies a time interval of

$$\Delta t = 24 \left[\frac{(\theta/0''.5)(D/\mathrm{kpc})}{(V/100\ \mathrm{km\ s^{-1}})}\right]\ \mathrm{yr}, \qquad (1)$$

where θ is the ring separation and D is the distance to NGC 6881.

Because the contrast between the rings and the background is lower in the torus than in the lobes, there is a possibility that the rings in the torus could be confused with regions between dark dust lanes. While we cannot rule this out completely, we do not believe that this is the cause of the observed rings in the torus, given the regular and symmetric forms of the observed rings.

Three knotlike structures (labeled as 1, 2 and 3 in Fig. 4) are also seen in the [N II] image. These knots have also been reported by Guerrero & Manchado (1998; labeled as A, B, and NW knot in their Fig. 2). A straight line connecting knots 1 and 3 roughly goes through the center of the torus (presumably the location of the central star). The distances between these two knots from the fiducial center of the torus are ∼11″.

4. DISCUSSION

The multipolar lobes observed resemble the point-symmetric structures seen in large nebulae such as KjPn 8 (López et al. 1995) and NGC 2440 (López et al. 1998). Similar structures have also been previously reported in the young PNs He 2-47 and M1-37 (Sahai 2000). The existence of more than one polar axis suggests simultaneous collimated outflows in more than one direction (Sahai & Trauger 1998) or that the outflow direction has changed with time (sometimes referred to as bipolar, rotating, episodic jets, or BRETs). For example, the morphology of NGC 6884 has been interpreted by a precessing outflow model (Miranda et al. 1999). For PPNs, multipolar lobes are known to be present in AFGL 618, which has high-velocity outflows in at least three different directions (Trammell & Goodrich 2002).

These results suggest that the fast outflows responsible for the shaping of PNs are not spherically symmetric but are highly collimated. These knots observed in NGC 6881 at both ends of the bipolar lobes may be related to the phenomenon of fast low-ionization emission regions (FLIERs) commonly observed in PNs (Balick et al. 1998). Although the origin of FLIERs are not definitely known, they can be the result of instabilities developed due to the change in magnitude, velocity, and direction of the fast outflow (Steffen et al. 2001), and NGC 6881 seems to possess these characteristics.

Ring structures associated with bipolar lobes were first seen in the *HST* image of SN 1987A (Crotts & Heathcote 2000 and references therein). Similar ring structures have also been detected in the PNs Hb 12 (Welch et al. 1999), He 2-113 (Sahai et al. 2000), MyCn 18 (Sahai et al. 1999), and He 2-104 (Corradi et al. 2001). While the rings in MyCn 18 have different sizes and can be interpreted as projections of the rims of a tilted hour glass, that is not the case for NGC 6881. The morphology of the two pairs of lobes in NGC 6881 are not as wide open as in MyCn 18. However, the H_2 imaging of NGC 6881 clearly shows a pair of open lobes extending well beyond the optical lobes (Guerrero et al. 2000). Maybe NGC 6881 will eventually evolve into a more open-ended morphology as the result of continued fast outflow from the center breaking open the closed ends. In the cases of He 2-113 and He 2-104, the rings are in the equatorial region, whereas in the other cases, the rings are in the lobes. NGC 6881 has rings in both regions, and their properties are not identical to the previous examples. The closest analog of these rings may be AFGL 618, where two rings can be seen in one of the lobes (Trammell & Goodrich 2002). Assuming a distance of 1.5 kpc and an outflow velocity of 120 km s^{-1}, Trammell & Goodrich (2002) derived a time interval of 35 years between lobes, which is very similar to the value we find for NGC 6881. The systematic, multiple rings seen in NGC 6881 show clearly that these rings are not a peculiar, isolated instance but could represent a common dynamical phenomenon in planetary nebulae.

These rings are two-dimensional structures and represent a different phenomenon to the concentric arcs seen in proto-PNs and PNs, which are spherical shells projected onto the plane of the sky (Kwok et al. 2001). These arcs are best illustrated in the PPN AFGL 2688, which has the highest number (23) of observed arcs (Sahai et al. 1998). Three sets of roughly equally spaced concentric arcs are seen in the halo of NGC 6881 (Corradi et al. 2004). Although Corradi et al. (2004) refer to them as "rings," we prefer to call them "arcs" so as not to confuse them with the two-dimensional rings discussed in this Letter.

When the rings in SN 1987A were discovered, they were first explained by the interacting winds model (Blondin & Lundqvist 1993). Later models included precessing jets in a binary system (Fargion & Salis 1995) or magnetic tension (Tanaka & Washimi 2003). After more double-ring systems were found in PNs, models were developed based on the interaction between a collimated fast outflow with a previously ejected episodic AGB wind (Soker 2002).

However, the multiring system in NGC 6881 goes beyond the double rings seen in SN 1987A. These multiple rings may also have been seen in the Red Rectangle, where they are seen almost exactly edge-on (Soker 2005). In the model of Soker (2002), if there are several impulsive AGB mass-loss episodes, then more double rings will form. Since the multiple arcs are density enhancements in the AGB envelope and could be the result of episodic mass loss, the multiple rings are the consequence of multiple arcs, according to this model. Support for this picture can be found in the fact that the four rings in each of the lobes are more or less evenly spaced, just as the case in the even spacings observed in circumstellar arcs. We also note that the three concentric arcs seen in the halo have spacings of $\sim 1''$ (Corradi et al. 2004), which are only slightly larger than the spacings of the rings in the lobes.

In the numerical simulations of collimated fast winds interacting with a preexisting AGB wind by Lee & Sahai (2003), multiple coaxial rings can be seen in their Figure 11, under their model 3 with a fast wind of 1000 km s^{-1} and an opening angle of 10°. These rings are different from those of NGC 6881 in one important aspect: they are not evenly spaced. According to Lee & Sahai (2003), these are rippled shells produced by a turbulent wind.

Most interestingly, the axis of the inner rings is aligned with the bipolar lobe B, whereas the axis of the outer rings is aligned with the lobes (A, A’). This raises the possibility that the torus has precessed since the ejection of lobes (A, A’) and that the bipolar lobes (B, B’) represent a later development. However, this seems to contradict the fact that the two pairs of lobes have similar sizes and therefore similar dynamical ages.

5. CONCLUSIONS

New *HST* observations reveal the existence of two-dimensional rings perpendicular to each of the two bipolar axes of NGC 6881. The observed quadrupolar morphology of NGC 6881 strongly suggests that the nebula is shaped by highly collimated fast outflows, whose orientation has changed suddenly sometime in the recent past. The observed two-dimensional rings could be the result of waves generated by the dynamical interaction between the fast outflow and the remnant AGB circumstellar material, the consequence of episodic, collimated fast outflows, or a collimated fast outflow interacting with discrete AGB shells. These results, together with other morphological features such as arcs, FLIERs, point-symmetric structures, etc., observed in other PNs, demonstrate that PNs are rich in dynamical phenomena and represent an ideal laboratory for the study of gas and dust dynamics.

This work is based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. These observations are associated with program 8307. We gratefully acknowledge helpful discussions with Noam Soker and Martin Guerrero, and assistance in image processing by Joanna Wong. We would also like to thank an anonymous referee for helpful comments. This work was supported in part by grants to S. K. from the Natural Sciences and Engineering Research Council of Canada and by the National Science Council of Taiwan. S. K. acknowledges the award of a Killam Fellowship from the Canada Council for the Arts.

REFERENCES

Aaquist, O. B., & Kwok, S. 1990, A&AS, 84, 229
Balick, B., Alexander, J., Hajian, A. R., Terzian, Y., Perinotto, M., & Patriarch, P. 1998, AJ, 116, 360
Blondin, J. M., & Lundqvist, P. 1993, ApJ, 405, 337
Corradi, R. L. M., Livio, M., Balick, B., Munari, U., & Schwarz, H. 2001, ApJ, 553, 211
Corradi, R. L. M., Sánchez-Blázquez, P., Mellema, G., Gianmanco, C., & Schwarz, H. E. 2004, A&A, 417, 637
Crotts, A. P. S., & Heathcote, S. R. 2000, ApJ, 528, 426
Fargion, D., & Salis, A. 1995, Nucl. Phys. B., 43, 269
Guerrero, M. A., & Manchado, A. 1998, ApJ, 508, 262
Guerrero, M. A., Villaver, E., Manchado, A., Garcia-Lario, P., & Prada, F. 2000, ApJS, 127, 125
Hua, C. T., Grundseth, B., & Maucherat, A. J. 1993, A&AS, 101, 541
Kwok, S., & Aaquist, O. B. 1993, PASP, 105, 1456
Kwok, S., Hrivnak, B. J., Zhang, C. Y., & Langill, P. P. 1996, ApJ, 472, 287
Kwok, S., Su, K. Y. L., & Hrivnak, B. J. 1998, ApJ, 501, L117
Kwok, S., Su, K. Y. L., & Stoesz, J. A. 2001, in Post-AGB Stars as a Phase of Stellar Evolution, ed. R. Szczerba & S. K. Górny (Dordrecht: Kluwer), 115
Lee, C.-F., & Sahai, R. 2003, ApJ, 586, 319
López, J. A., Meaburn, J., Bryce, M., & Holloway, A. J. 1998, ApJ, 493, 803
López, J. A., Vázquez, R., & Rodríguez, L. F. 1995, ApJ, 455, L63
Manchado, A., Stanghellini, L., & Guerrero, M. A. 1996, ApJ, 466, L95
Miranda, L. F., Guerrero, M. A., & Torrelles, J. M. 1999, AJ, 117, 1421
Sahai, R. 2000, ApJ, 537, L43
Sahai, R., Nyman, L. Å., & Wootten, A. 2000, ApJ, 543, 880
Sahai, R., & Trauger, J. T. 1998, AJ, 116, 1357
Sahai, R., et al. 1998, ApJ, 493, 301
———. 1999, AJ, 118, 468
Soker, N. 2002, ApJ, 577, 839
———. 2005, AJ, 129, 947
Steffen, W., López, J. A., & Lim, A. 2001, ApJ, 556, 823
Su, K. Y. L., Volk, K., Kwok, S., & Hrivnak, B. J. 1998, ApJ, 508, 744
Tanaka, T., & Washimi, H. 2003, in IAU Symp. 209, Planetary Nebulae: Their Evolution and Role in the Universe, ed. S. Kwok, M. Dopita, & R. Sutherland (San Francisco: ASP), 503
Trammell, S. R., & Goodrich, R. W. 2002, ApJ, 579, 688
Welch, C. A., Frank, A., Pipher, J. L., Forrest, W. J., & Woodward, C. E. 1999, ApJ, 522, L69