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A WIND-BLOWN BUBBLE MODEL FOR NGC 6543

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ABSTRACT

Detailed kinematic observations of the bright inner portion of the planetary nebula NGC 6543 are presented. These data, combined with imaging observations reported by Balick *et al.* (1987), show that the kinematics of the nebula are just as peculiar as its morphology. The two crossed elliptical filaments seen in $H\alpha$ and high-ionization forbidden lines appear to be expanding radially at projected velocities of ~ 20 km s^{-1} through an otherwise quiescent medium. North and south of the bright nebulosity are two bright low-velocity "caps" characterized by very peculiar ionizations and/or chemical abundances. Surrounding each cap and extending into the large, knotty halo that surrounds the bright nebula are two "tails" typified by velocities from 25 to 35 km s^{-1}. Empirically, we find that a double bipolar model readily incorporates most observational information regarding the complex structure and kinematics of NGC 6543. We propose that fast winds from the central star of NGC 6543 interact hydrodynamically with the denser red giant envelope expelled earlier, as suggested by Kwok (1982) and others. Wind-driven shocks seem to create two pairs of bipolar lobes along nearly orthogonal axes. The bright ellipses arise near the lobe interfaces where slow nebular expansion causes shocks at the lobe boundaries to converge obliquely. The presence of the caps and tails is not well incorporated by this model. The formation of a double bipolar nebula, though not without precedent, seems difficult to understand unless the stellar winds are collimated, precessing, episodic, or a combination of these.

I. INTRODUCTION

Interaction between the high-velocity wind of a planetary nebula nucleus (hereafter referred to as PNN) and the surrounding former red giant envelope (RGE, also sometimes called the "slow wind") is an important element in understanding the morphological evolution of planetary nebulae (hereafter referred to as PNs; e.g., Kwok 1980, 1982; Kwok *et al.* 1985; Kahn 1983; Kahn and West 1985; Okorokov *et al.* 1985; Volk and Kwok 1985; Balick 1987a,b). Many PNNs are losing mass at rates often as high as $10^{-7} \mathscr{M}_\odot$ per year and at velocities of several thousand km s^{-1} (hereafter referred to as the "fast wind"; Cerruti-Sola and Perinotto 1985). The momentum carried by the fast wind is comparable to that in the RGE. Since the two winds are strongly coupled, the fast winds will continuously modify the structure of PNs. Signs of the interaction between the fast wind and the former RGE should be visible in the sharp-edged ionization boundaries characteristic of a "snowplow" shock, as shock-heated filaments, etc.

The morphology of most PNs falls into three nondistinct groups (Balick 1987b). A very small fraction have circular symmetry (e.g., IC 3568, NGC 1535, NGC 6894). More typically, PNs are elongated with a distinct major axis. A second group of PNs are elliptical in shape (NGC 3242, 7662 and IC 418). The third group are the butterflies such as M2-9, Hu 5, and NGC 2346. The last two groups are typified by relatively high densities along their minor axes, and all may eventually be understood in terms of the interaction between a possibly collimated fast wind with an asymmetric RGE (e.g., Kahn and West 1985).

A very few PNs do not fit into the morphological classes and types defined by Balick (1987b). Of these, one of the most striking and best studied is NGC 6543 (e.g., Balick *et al.* 1987—hereafter referred to as Paper I; Phillips *et al.* 1977; Munch 1968; Bianchi *et al.* 1987; see also the color picture in Balick 1987a). Bianchi *et al.* find that NGC 6543 has a WR-type central star of effective temperature $\sim 80\,000$ K, mass-loss rate of $3.2 \times 10^{-7} \mathscr{M}_\odot$ yr^{-1}, wind terminal velocity of 1900 km s^{-1}, and distance of 1390 pc. As shown in Paper I, the stellar wind alone can easily account for both the nebular luminosity and momentum. Therefore, stellar winds are likely to be of critical importance in the understanding of the nebular shape and evolution. Some observational support for this conclusion is presented in Paper I.

At first glance, the nebula appears as a pair of crossed ellipses in projection on the sky. The putative three-dimensional morphology has been described as a triaxial spheroid (Phillips *et al.* 1977) and condensations on helical sheets (Munch 1968). Hippelein *et al.* (1985) attempted to match a simple wind-blown bubble model to observations of NGC 6543. Later in this paper we suggest another model. The spatial and kinematic observations of NGC 6543 show that it is far more complex than published models of PN evolution predict.

Here, we focus both on the details of the spatial and kinematic structure of NGC 6543 and the extent to which wind-shaping explains its unusual morphology. We shall find that the structure of NGC 6543 is nicely described by a simple empirical model, but that the model seems awkward (though not impossible) to accommodate within the context of simple hydrodynamic processes.

II. OBSERVATIONS

Imaging and kinematic data are the key to understanding the present morphology of NGC 6543. The set of imaging data consists of several optical and subarcsecond radio images that were presented and described in Paper I. In addition, optical images were obtained in May 1985 using the

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CCD Direct Camera on the 2.1 m telescope of the Kitt Peak National Observatory of NOAO under conditions of variable transparency and 1 arcsec seeing. NGC 6543 was observed in the light of Hα λ 6563 Å, [O I] λ 6300 A, [N II] λ 6584 Å, and [O III] λ 5007 Å. The observations were more fully described by Balick (1987b). Pixels project to 0\.″38 on the sky. The optical images, each covering a 75″ patch of sky centered on NGC 6543, are shown in Fig. 1 [Plate 79].

In this paper we present new kinematic data. NGC 6543 was observed with the echelle spectrograph (long-slit mode) and TI2 CCD detector at the KPNO 4 m telescope in April 1986. The seeing was 1\.″5, and the transparency was excellent throughout the observations. The width of the north–south slit was 1″. All observations were 150 s in duration. Each of the 800×800 array of 15 μm pixels corresponds to 4.45 km s^{-1} in the dispersion direction and 0\.″33 along the slit.

The inner bright portion of the nebula (inner 20″) was mapped simultaneously in the lines Hα and [N II] by stepping the slit across the nebula from west to east in 2 arcsec intervals. The data were corrected for instrumental effects using software available at NOAO. All of the data were then digitally smoothed and repacked into a three-dimensional data "cube" using the AIPS image-processing program, where the axes are right ascension, declination, and velocity. The data were then plotted as R.A., Dec. images of intensity, one such image for each 8.9 km s^{-1} velocity interval (2 pixels) along the velocity axis. The present data are similar to those presented by Munch (1968), although the newer observations have better sensitivity, improved dynamic range, and wider sky coverage than those reported by Munch.

These images in narrow ranges of radial velocities (hereafter referred to as the "isovelocity images") are shown in Fig. 2. Velocities are indicated with respect to the median radial velocity of the nebula. The figure shows that there are no major differences in the velocities of common Hα and [N II] features. However, the Hα lines are far more affected by thermal broadening than are [N II] lines, so distinct kinematic features are more easily recognized in the [N II] velocity images. The names and velocities of prominent [N II] features are indicated in Fig. 3. Other regions of [N II] emissions in NGC 6543 whose velocities are not shown in the figure have nearly zero velocity with respect to the median.

III. NEBULAR FEATURES

a) Spatial Structure of NGC 6543

The Hα and λ 20 cm images of NGC 6543 resemble two nearly perpendicular crossed ellipses, each centered on the central star. A smooth, elliptically symmetric background of Hα and [O III] nebulosity envelops the ellipses (which led Phillips *et al.* (1977) to conclude that the nebula has a triaxial spheroidal shape). However, the shape of the nebula revealed in emission lines of low ionization is dramatically different from that seen in Hα, [O III], or the radio continuum (see Fig. 1). For example, only one of the two ellipses is clearly visible in low-ionization lines. The bright [N II] caps have no Hα or [O III] counterparts whatsoever! Note that the VLA images with high spatial resolution (Paper I) show the two crossed ellipses to have kinks and bends.

Based on kinematic data, Munch suggested that the ellipses are, instead, a pair of spiral filaments which intersect in projection on the sky. He proposed a model in which the spirals represent a pair of helices expanding along the line of

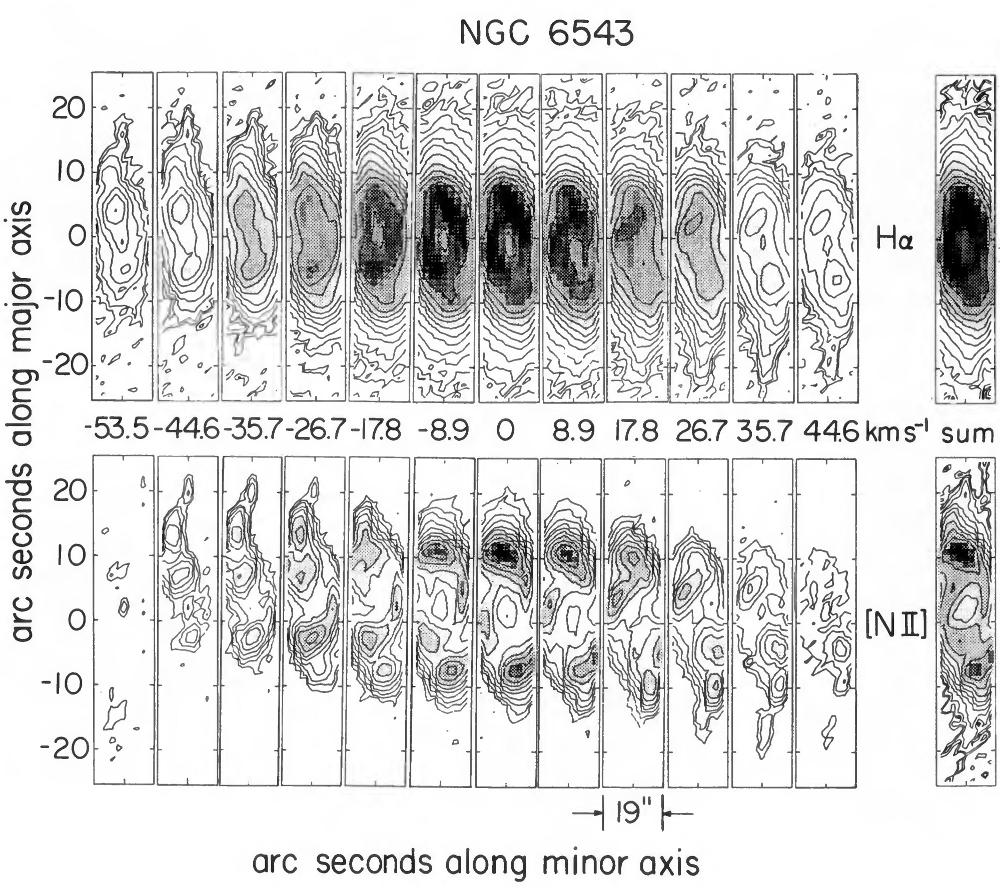

FIG. 2. Isovelocity images of NGC 6543 in Hα and [N II]. Image pixels are 2″ along the minor axis (east–west) and 1″ along the major axis north–south). Adjacent images are separated in velocity by 8.9 km s^{-1}. All velocities are measured with respect to the median nebular velocity. Each contour represents an intensity change of a factor of 2. The images on the far right are the summation of all velocity images for a given emission line. These should generally reproduce the corresponding direct images taken through 10–15 Å filters (Fig. 1).

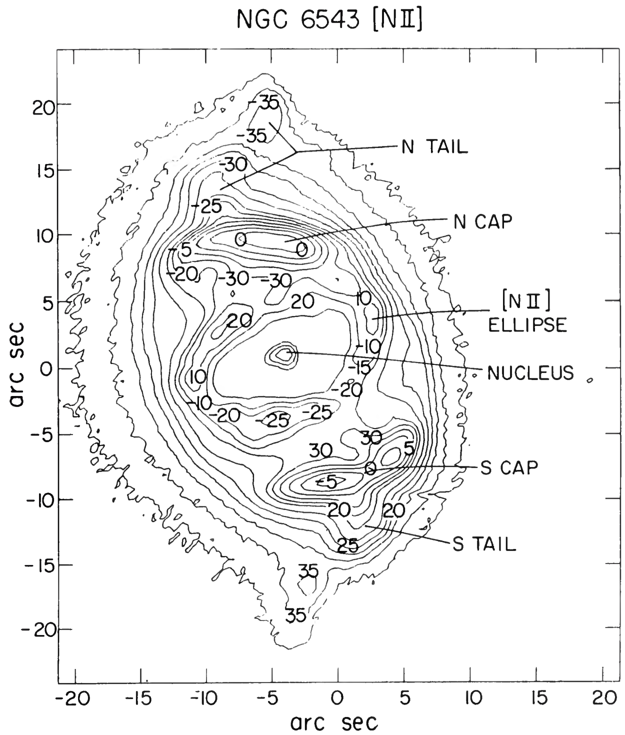

FIG. 3. The names and velocities of key nebular features seen in the [N II] line are shown on a contour map of the lower left-hand panel of Fig. 1. The lowest seven contours are spaced by factors of 2 in intensity, and the remainder are spaced by factors of $2^{1/2}$.

sight. However, such a model fails to account for the striking differences seen in the lines of low and high ionization, for the kinks and bends, or for the very small cross section of the spiral filaments. Moreover, Munch's model suggests ballistic motions of particles along the helical filaments, motions that are not observed.

We propose instead an empirical model for the structure of NGC 6543 which consists of two pairs of bipolar lobes. The symmetry axes of the lobe pairs have different orientations and intersect at the central star. A sketch of the model is shown in Fig. 4. *We emphasize that the model shown in Fig. 4 is motivated strictly by the appearance of NGC 6543.*

The loci of lobe contacts form a pair of closed, crossed, quasi-elliptical figures when projected onto the sky. Kinks in the ellipses appear in the VLA images as expected at the NE and SW crossing points. The thin, weakly radiating surfaces of the lobes match extremely well with the outline of the VLA maps and the Hα images shown in Paper I.

The prominent [N II] caps are associated with the outer edges of the NE and SW lobes. Near the caps and extending into the very large, knotty halo around the inner nebula (Millikan 1974) are two tails that appear to be twisted jet-like features wound along an axis perpendicular to a plane containing the bright [N II] ellipse. The tails are visible in all four frames of Fig. 1, and are particularly prominent in the lines of lowest ionization. The large halo that surrounds the bright inner nebulosity is not visible in these pictures. The physical relationship of the caps and tails to the model shown in Fig. 4 is not obvious, although their situation at the edges of the NE and SW lobes suggests that they may be caused by the same process that formed the lobes.

b) Kinematic Structure

The pattern of kinematics that is seen in the lines of Hα and [N II] is clearly ordered and yet very complex. The present discussion shall focus on the kinematics of structural features identified above; *to wit* the lobes, the interfaces, the caps, and the tails (see Fig. 3).

The lobes show little deviation from the median nebular velocity to within 10 km s^{-1}. However, the lobes are very faint in the [N II] line. In Hα, the thermal linewidth is of order 20 km s^{-1}. For both reasons, any expansion or other systematic motion in the lobes is difficult to discern.

The [N II] ellipse shows a clear pattern of expansion outward from the nucleus. The line of nodes is also the major axis. Along the minor axis, the projected expansion speed is about 20 km s^{-1}, with the south side approaching. If the ellipse is a tilted circular feature, then the true expansion velocity is about 30 km s^{-1}. The other ellipse is seen only in Hα and [O III]. In the echelle data, this ellipse projects onto regions of complex Hα line profiles. Arguably, it appears that the north and south extremes of the ellipse show no radial motions. Along the minor axis there may be a systematic expansion of about 20 km s^{-1} (west side approaching); if so, then the true expansion speed is ~ 30 km s^{-1} if the north–south ellipse deprojects to a circle. In summary, the kinematics of both ellipses appears to be very similar.

Like the lobes, the bright [N II] caps have little if any net observable motion. Even so, their placement at the projected

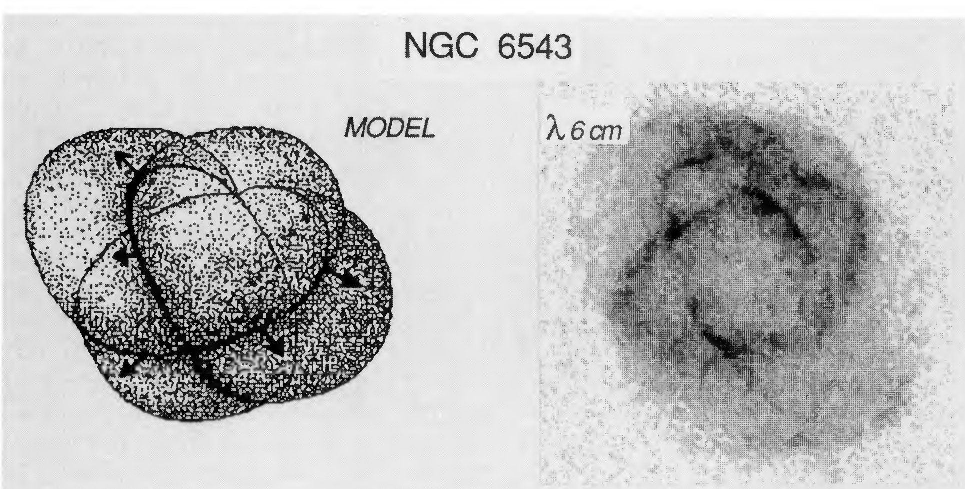

FIG. 4. Schematic of a model for the physical structure of NGC 6543, consisting of two pairs of bipolar lobes on axes that intersect at the nucleus. The quasi-elliptical figures represent the loci where adjacent lobes meet. The darker lines represent loci in the nebular foreground that are expected to have negative radial velocities. Mottling is used to suggest the three-dimensional shape of the foreground nebular surface. For comparison, the λ 6 cm VLA map from Paper I is shown to a similar scale as that of the model.

edge of the nebula argues that they could have a significant space velocity with respect to the nucleus. For comparison, the very strong [N II] and [O I] lines emitted by the caps, if indicative of solely collisional heating, would suggest a shock velocity of about 100 km s^{-1} or more. A more complete discussion of the heating and ionization of the caps is presented in Paper I.

The tails show large projected radial motions of 30–40 km s^{-1} (north tail approaching). The true space velocity might be much higher, depending on the inclination angle to the line of sight. Kinematically, the tails appear to be material outflowing near the symmetry axis of the [N II] ellipse. As seen in Figs. 2 and 3, gas with about the same Doppler shift as the tails can be found on both sides of the caps. In projection, the tails extend deep inside the nebula. However, there is a strange absence of any velocity components ~20–40 km s^{-1} in the direction of the caps. Clearly, the caps and the tails are distinct kinematic features which are somehow physically associated.

IV. INTERPRETATION

a) General Remarks on PNs

Although NGC 6543 is singular in its overall appearance, other PNs share one or more of its peculiar characteristics. The common occurrence of various forms of bipolarity in PNs argues that similar physical processes—allegedly due to the hydrodynamical influence of the fast stellar wind that overtakes and interacts with the former envelope of the central star—continuously alter the shape of PNs. Consequently, a detailed understanding of the morphological features of NGC 6543 can provide important clues to the processes that form and shape other PNs.

The novitiate of astronomy is taught that PNs are, with rare exceptions, round. Certainly, a few PNs fit this description, and their structures can probably be described by simple one-dimensional hydrodynamic models (Kwok and his collaborators, Okorokov *et al.* 1985; Volk and Kwok 1985; etc.). However, the vast majority of PNs, including NGC 6543, show that spherically symmetric models of PNs are highly simplistic. As discussed in Sec. I, the typical PN has a very obvious major axis, and a few PNs (including NGC 6543) are far more complex than even butterfly nebulae. We elect to open the discussion of the shapes of PNs with the butterfly PNs since, in this class of objects, the conditions that produce the structure are believed to be qualitatively understood.

The formation of butterfly nebulae has received great attention in the past few years, principally in the context of young stars (Lada 1985) and stars in various evolutionary stages (Cohen 1983, 1987). Any dense disk near the central star of a bipolar can be expected to collimate the stellar wind and form a bipolar nebula (e.g., Icke and Choe 1987). Since several compact PNs are highly bipolar (M2-9, Hubble 5, NGC 2346, IC 5217), we can expect that similar processes operate for evolved stars, although the origin of the disks around pre-main-sequence stars and PNNs could be very different.

A close binary system can generate a relatively dense equatorial "waistband" (Kolesnik and Pilyugin 1986) which, in turn, can collimate the fast wind. Such disks could lead to some degree of collimation of the wind from the nuclei and explain the characteristic nonspherical shapes of PNs (Kahn and West 1985). However, the general prolate shapes, frequent occurrence of ansae and asymmetric flow, and mild bipolarity of nearly all PNs beg a more universal explanation than close binaries, especially since very few (five or six) PNN are known to be in multiple star systems (and, interestingly, only one of the binary nuclei is found in a bipolar PN!).

The disks in pre-main-sequence stars are expected as a natural consequence of their formation (e.g., Pudritz and Norman 1986). It is conceivable that portions of these disks manage to survive while a star or its companion evolves through the red giant phase and becomes a PN. Such an explanation might apply to NGC 2346 since the unseen PNN has an A type main-sequence companion, suggesting that the timescale to the PN stage could be short compared to the evolution timescale of the accretion disk formed with both of the stars.

Zuckerman and Gatley (1987) have found a disk of molecular hydrogen around NGC 2346 and other PNs. They argue that bipolar and butterfly PNs are found preferentially at low Galactic latitudes, and are thus probably associated with stars whose main-sequence masses are relatively large. We surmise that such stars also have the shortest evolution timescales, and might be the most likely candidates to evolve to the PNN stage before their nascent disk of formation dissipates. Hence disks may very well have been in place in some PNs long before the PNN evolved from the red giant phase.

Whatever their origin, relatively dense equatorial bands may surround many PNs. Extreme cases of "density contrast" between equator and pole may give rise to the relatively rare butterfly PNs. More often, the density contrast is low enough that the equator is ionized by the central star, and the higher-density disk is seen as a brightness enhancement along the minor axis of the RGE (e.g., NGC 3242, 6826, 7662). The higher pressure along the equatorial plane can have a significant influence on the propagation of the fast wind into the external environment (e.g., Kahn and West 1985) and can lead to the formation of the commonplace prolate and bipolar PNs.

b) Wind-Shaped Lobes

Suppose the medium (i.e., the RGE) into which the fast wind blows has an equatorial mass concentration producing a density gradient that varies with latitude. This "shell" moves outward for some time at a velocity of about 20 km s^{-1} into the surrounding material. After several expansion timescales, a high-velocity wind begins from the exposed core. *IUE* spectra indicate that the fast wind has a velocity of about 2000 km s^{-1} (e.g., Pottasch 1984), and will quickly encounter and shock against the shell that contains it.

As described by Kwok *et al.* (1978), Kwok (1982, 1985), Kahn (1983), Kahn and West (1985), and Okorokov *et al.* (1985), the shock structure will have two components, one driving outward into the slow-moving shell, and one due to the change in velocity the trapped wind must undergo as it reaches the shell. The layer of wind-deposited gas downstream from this inward-facing shock will thermalize the kinetic energy of the wind and the layer will quickly become very hot (10^6 K) and will swell inward until the inner shock front is very close to the surface of the star. Details of this rapid evolutionary process have been computed only for one-dimensional geometries—geometries that clearly do not pertain to NGC 6543. Until two-dimensional calculations become available, we do not endeavor to match observations with models.

In this manner the central region of the nebula becomes filled with a very hot gas of low density. The outward-facing shock sweeps up matter as it expands, increasing the density directly behind the shock front in a very thin cooling layer. Although pressure is continuous across the interface between the hot bubble and the cooling swept-up gas, the density is discontinuous (the interface is the "contact discontinuity"). The contact discontinuity is always so close to the outward-facing shock front that the two can be considered to be traveling outward into the RGE together.

When the high-speed wind begins to push into the RGE, it will encounter more resistance to expansion in the equatorial region than in the polar directions. Thus the outward-facing shock will deform into a single pair of lobes with an increasingly elliptical shape (Kahn and West 1985). This elliptical shape will tend to focus the postshock flow as the wind passes through the inward-facing shock, resulting in increasing elongation of the central cavity and the deposition of most of the momentum in a narrow cap around the pole (Icke 1986). The velocity difference between the expansions of the polar and equatorial regions can continue to increase to the point where the shock becomes detached from the walls of the cavity at large oblique angles, which could result in a brightness profile and morphology similar to that of M2-9 (Icke and Choe 1987).

c) Scenarios for the Evolution of NGC 6543

The discussions above apply to an idealized PN. Balick (1987b) has discussed the shapes of PNs in general and argues that they are generally in accord with the expectations of the interacting-winds model for the evolution of PNs. However, he identifies NGC 6543 as one of a very few PNs with "peculiar" morphology, and notes that such PNs merit special consideration. This is our immediate goal here. We explore whether our strictly empirical model for NGC 6543 (Fig. 4) can be reconciled with interacting-winds models.

The two pairs of lobes in our strictly empirical model for NGC 6543 can be reconciled with the models if we assume that (1) each pair of lobes were formed at different times and (2) along axes at different position angles. These assumptions are *ad hoc*. Implicit in the first of these assumptions is that lobe formation is episodic. The second assumption requires that some mechanism collimates the fast wind and forces its ejection axis to precess. (The second assumption might be true if the fast-wind ejection axis precesses owing to torques applied to the nucleus by companion star(s).) We would thus expect the two pairs of lobes in Fig. 4 to have different ages, and perhaps different kinematics as well. Either (or both) pair of lobes may be expanding. The kinematic data, within their limitations, are consistent with this picture.

Another model is that the NE and SW lobes were formed in the same manner as other PNs, and the NW and SW "lobes" in Fig. 4 are actually portions of a remnant of the dense RGE disk ejected at the onset of the PN phase. This model has the advantage of simplicity and axial symmetry but is not as visually clear as two pairs of bipolar lobes. In time, the wind-blown lobes expand outward as depicted from left to right in Fig. 5. The apparent perpendicularity of the lobe axes is a natural consequence of this model. However, we must assume that the dense remnant of the RGE is not presently toroidal, as shown schematically in Fig. 5. Moreover, there is no indication from the optical or radio images that the NW and SE lobes are any denser than the NE–SW pair of lobes.

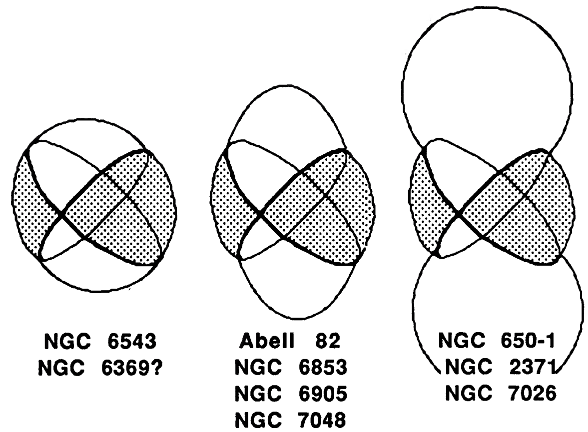

FIG. 5. Schematic models of nebulae whose structure might be related to that of NGC 6543. Conceivably, though not necessarily, the panels represent different evolutionary stages for this morphological class of planetary nebula.

Both models successfully account for the formation of the bright crossed ellipses. If either pair of lobes is expanding (or if both are), then near the contact interfaces the gas along the surface of one lobe converges and collides with gas along the front of the adjacent lobe. (The action is like that of particles on the blades of a closing scissors). In the convergence zone the gas is heated and, at the same time, is pushed radially outward, as indicated by arrows in Fig. 4. In this manner, the high surface brightness and relatively large expansion velocities of the crossed ellipses can be explained. However, the second model has the drawback that other PNs of the same general morphological type do not exhibit crossed ellipses at the interfaces between their lobes and disk remnants. This suggests that the morphology and evolution of NGC 6543 are highly unusual, or that NGC 6543 is in a very special, short-lived phase of its evolution.

On the other hand, neither model easily accounts for the peculiar low-ionization caps and tails. Compared to the nebulosity that surrounds them, the caps have anomalously low ionization and/or very strange abundances. Spectrophotometric studies of the caps are certain to yield interesting results. The tails seem to be different manifestations of flow convergence as described above. Numerical hydrodynamical models may help to reveal how caps and tails are formed and heated.

d) A Binary Nucleus?

By analogy to SS 433, the equal and opposite bends in the tails of NGC 6543 raise the possibility that the collimated winds precess on a timescale comparable to, though somewhat shorter than, the expansion time of the nebula.

One obvious possibility is that the central star of NGC 6543 is a precessing binary. Several observers have suspected NGC 6543 of possessing a binary nucleus (Livio 1982; Acker 1976; Lutz 1978a,b). Light variations have been detected with possible periods as short as 0.06 days, but the variations were not subsequently confirmed (Patterson 1979a,b; Gilra *et al.* 1978). As yet, the existence of a binary is unsubstantiated. However, the observational problems of detecting this type of system are so great that we shall pursue the possible implications of the existence of a binary.

We conjecture that the tails might be "bullets" fired along a precessing axis related to the precession of the binary. (Ironically, this is the same sort of model proposed by Munch (1968) for the ellipses in NGC 6543!) Judging from the wiggles in the tails, the tilt of the "gun" from its axis of precession is $\sim 10°$ or $15°$. Intriguingly, the precession axis appears to be perpendicular to the plane of the [N II] ellipse.

V. CONCLUSIONS

The structure and kinematics of the planetary nebula NGC 6543 suggest an empirical model for the nebula which consists of two pairs of lobes along nearly perpendicular axes. The concentric, crossed elliptical filaments are associated with the loci of lobe contact interfaces. The outline of the lobes predicted by the model is in complete agreement with the observations of the nebula seen in the radio continuum in the light of Hα and [O III].

Compared to all other carefully studied PNs, the complexity of the morphology and kinematics of NGC 6543 makes this PN somewhat of a enigma, with little apparent respect for the standard notions of how PNs are shaped. We suggest, though we cannot substantiate, that the physical processes that shape this nebula are the same ones that operate in most other PNs, and that the uniqueness of NGC 6543 derives from unusual circumstances (boundary conditions) close to its nucleus. Nonetheless, the caps and tails seen in NGC 6543 are simply unexpected based on available hydrodynamic models of PN evolution.

A firm physical basis for the empirical model of NGC 6543 must await detailed, multidimensional hydrodynamical models which we intend to develop in the near future. A binary nucleus appears now to be the most promising research direction to explain the complexities of the morphology of NGC 6543, especially its oppositely trailing tails, their relationship to the "stationary" [N II] caps, and the possible existence of two distinct pairs of bipolar lobes.

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REFERENCES

Acker, A. (1976). Publ. Obs. Astron. Strasbourg **4**, fasc. 1.
Balick, B. (1987a). Sky and Telesc. **73**, 125.
Balick, B. (1987b). Astron. J. **94**, 671.
Balick, B., Owen, R., Bignell, C. R., and Hjellming, R. M. (1987). Astron. J. **94**, 948 (Paper I).
Bianchi, L., Cerrato, S., and Grewing, M. (1987). Astron. Astrophys. (in press).
Cerruti-Sola, M., and Perinotto M. (1985). Astrophys. J. **291**, 237.
Cohen, M. (1983). In *Planetary Nebulae*, IAU Symposium No. 103, edited by D. R. Flower (Reidel, Dordrecht), p. 45.
Cohen, M. (1987). Preprint.
Gieseking, F., Becker, I., and Solf, J. (1985). Astrophys. J. Lett. **295**, L17.
Gilra, D. P., Pottasch, S. R., Wesselius, P. R., and van Druinen, R. J. (1978). Astron. Astrophys. **63**, 297.
Hippelein, H. H., Baessgen, M., and Grewing, M. (1985). Astron. Astrophys. **152**, 213.
Icke, V. (1986). Astron. Astrophys. (submitted).
Icke, V., and Choe, S.-U. (1987). Astron. Astrophys. (submitted).
Kahn, F. D. (1983). In *Planetary Nebulae*, IAU Symposium No. 103, edited by D. R. Flower (Reidel, Dordrecht), p. 305.
Kahn, F. D., and West, K. A. (1985). Mon. Not. R. Astron. Soc. **212**, 837.
Kolesnik, I. G., and Pilyugin, L. S. (1986). Astron. Zh. **63**, 279.
Kwok, S. (1980). J. R. Astron. Soc. Can. **74**, 216.
Kwok, S. (1982). Astrophys. J. **258**, 280.
Kwok, S., Purton, C. R., and Fitzgerald, M. P. (1978). Astrophys. J. Lett. **219**, L125.
Kwok, S., Purton, C. R., Matthews, H. E., and Spoelstra, T.A.T. (1985). Astron. Astrophys. **144**, 321.
Lada, C. J. (1985). Annu. Rev. Astron. Astrophys. **23**, 267.
Livio, M. (1982). Astron. Astrophys. **105**, 37.
Lutz, J. H. (1978). In *Planetary Nebulae: Observations and Theory*, IAU Symposium No. 76, edited by Y. Terzian (Reidel, Dordrecht), pp. 185, 212.
Millikan, A. G. (1974). Astron. J. **79**, 1259.
Munch, G. (1968). In *Planetary Nebulae*, IAU Symposium No. 34, edited by D. E. Osterbrock and C. R. O'Dell (Reidel, Dordrecht), p. 259.
Okorokov, V. A., Shustov, B. M., Tutukov, A. V., and Yorke, H. W. (1985). Astron. Astrophys. **142**, 441.
Patterson, J. (1979a). IAU Circ. No. 3377.
Patterson, J. (1979b). IAU Circ. No. 3398.
Phillips, J. P., Reay, N. K., and Worswick, S. P. (1977). Astron. Astrophys. **61**, 695.
Pottasch, S. R. (1984). *Planetary Nebulae* (Reidel, Dordrecht).
Pudritz, R. E., and Norman, C. A. (1986). Can. J. Phys. **64**, 501.
Reay, N. K., Atherton, P. D., and Taylor, K. (1983). Mon. Not. R. Astron. Soc. **203**, 1087.
Shields, G. A. (1980). Publ. Astron. Soc. Pac. **92**, 418.
Volk, K. M. and Kwoks, S. (1985). Astron. Astrophys. **153**, 79.
Zuckerman, B., and Gatley, I. (1987). Astrophys. J. (in press).

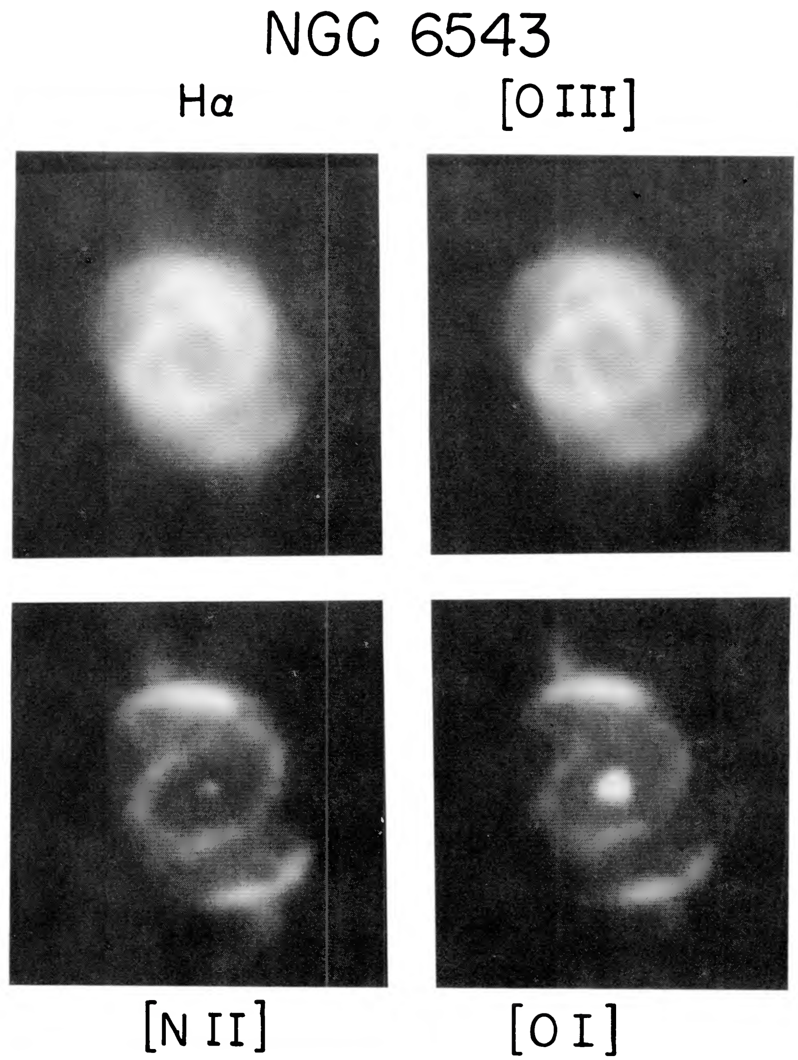

FIG. 1. CCD images of NGC 6543 (see the text). The contrast has been adjusted to show both the highlights and faint regions of the nebula.

B. Balick and H. Preston (see page 959)

