INTERNAL MOTIONS IN THE PLANETARY NEBULA NGC 6543

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1. Introduction

The planetary nebula NGC 6543 has been described (Curtis, 1918) as "quite irregular, of helical form". Its high surface brightness and its dimensions ($16'' \times 22''$ of arc) make it an ideal object for observation with the multislit technique used by Wilson (1950) to study other planetaries. In fact, had NGC 6543 been accessible to the 100-inch Mount Wilson Coudé, undoubtedly it would have been included in Wilson's survey. The interest in NGC 6543 arises from the fact that no information is available regarding the motions in a planetary nebula with some sort of helical appearance. The obvious question that arises in this respect is whether the nebular material is actually arranged in space on an open helix, rather than in a flat spiral. The related problems of its lifetime and stability also may be elucidated by studying in detail the internal motions.

2. Observations

Two multislit spectrograms of NGC 6543 were obtained with the 72-inch camera of the Palomar Coudé spectrograph. With an exposure of 90 min, measurable images in the N1 and N2 lines of O^{++}, in Hβ, in $\lambda\lambda$3868 and 3967 of Ne^{++} and in $\lambda\lambda$3726–29 of O^{+} are reached. The multislit unit is the same as that used by Wilson *et al.* (1959) to study the Orion Nebula. The projected width of each slit is 0·015 mm or 0·068 Å, and the slit spacing (1·0 mm) corresponds to 1''.32 of arc in the plane of the sky. The slits were oriented by means of the field rotator, North–South in one plate and East–West in the other. The exciting star in both cases was centered on the central slit, by reference to a fiducial mark readily identifiable on the images of that slit.

The measurements of apparent wavelengths were carried out by referring micrometer settings at points separated by 0·2 mm along every slit to the comparison spectrum, in the manner described by Wilson *et al.* (1959). Thus, radial velocities for the lines of O^{++}, Ne^{++} and O^{+} have been obtained for a square grid of points covering the nebula with 1''.32 spacing. Tables 1, 2, and 3 give the radial velocities of these lines, the points to which they refer being identified by rectangular equatorial coordinates measured in integral units of the spacing and with origin at the central star.

The intrinsic widths of the nebular lines are appreciably larger than the instrumental profile and vary considerably from place to place. In certain areas the lines can be clearly

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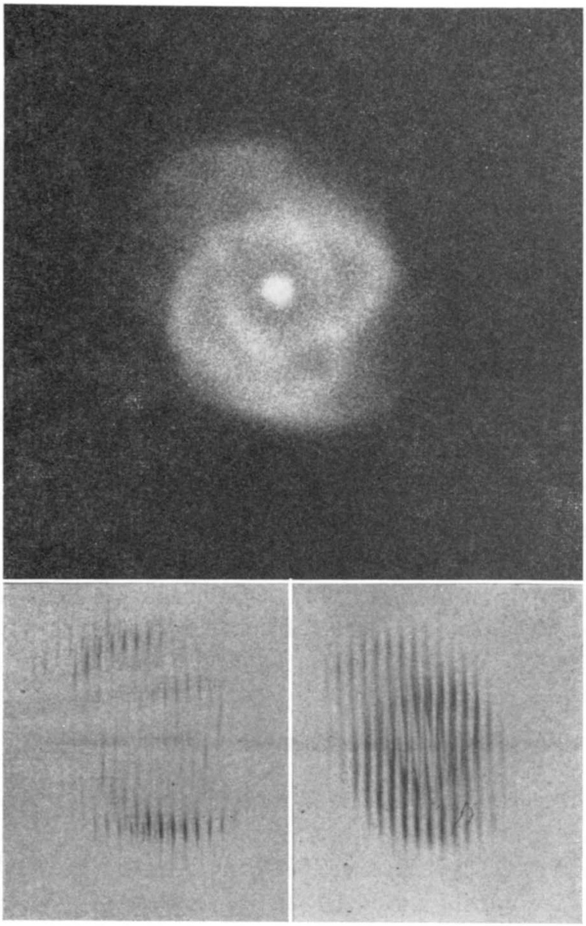

FIG. 1. *Image of NGC 6543 in radiation of the* [*O* III] *N1 and N2 lines at top. Multislit images in* [*O* II] *λλ3726–28 (left) and* [*Ne* III] *λ3867 (right) at bottom. In all images North is towards bottom and East to right.*

seen as double, and in a few points in the Ne^{++} images three components can be seen. This is why some entries in the tables contain more than one number. At those points where the lines appeared broad but unresolved, no attempt has been made to allow for blending effects in the radial velocities, but some idea of their importance can be gained by comparing the values with those of neighboring points. The general appearance of the O^{++} and Ne^{++} images is very similar and their radial velocities are nearly identical. The O^{+} image, unlike the images in lines of higher excitation, is densest in the outer regions. The radial velocities of O^{+} at those points where it is reasonably certain that there is no blending, nevertheless, agree with those of the

Table 1 *

Radial velocities of [O III] λ5006·85 Å

	E_7	E_6	E_5	E_4	E_3	E_2	E_1	EOW	W_1	W_2	W_3	W_4	W_5	W_6	W_7
N7	–	94·	97·4	95·9	95·1	94·6	93·3	95·1	93·6	?	92·4	–	–	–	–
N6	98·0	98·2	97·0	96·8	90·6	85·3	85·7	87·4	88·2	87·4	86·8	89·	–	–	–
N5	88·2	88·2	91·0	87·5	84·9	84·4	77·6	80·2	83·3	85·4	86·6	83·2	82·0	–	–
N4	83·6 –	83·7 –	86·7 –	91·2 66·2	87·8 66·2	84·8 61·3	75·4	76·0	79·6	84·8	86·1	85·8	81·5	77·4	–
N3	78·2 –	78·1 –	81·5 –	81·8 60·8	82·2 58·5	80·7 61·3	75·0	76·0	79·4	82·5	85·8	84.8	81·8	80·3	81·0
N2	– 74·6	– 73·4	– 77·1	– 76·4	– 75·8	95·3 62·8	90·6 62·3	87·8 62·3	86·6 65·6	88· 67·2	87·9 67·6	81·5	80·7	78·6	79·8
N1	– 70·6	– 69·2	– 71·0	– 71·8	– 65·0	89·7	87·	85·6	81·8	80·4	86·6 66·4	78·0	74·0	72·2	74·8
NOS	66·0	65·4	66·0	69·0	87·6 64·0	100·2 58·2	99·	95·2	91·2	81·8	89·8 69·0	90·4 65·0	71·4	71·0	69·0
S1	62·6	61·4	62·2	63·5	66·4	79·4 51·7	87·4 45·8	86·4 43·2	82·6 –	78·2 –	76·2 –	86·1 62·0	88·2 61·6	– 63·4	– 68·8
S2	62·4	61·2	58·1	60·1	63·9	70·0 51·6	73·1 48·8	74·5 44·	74·9 –	73·0 –	71·1 –	79·9 60·9	80·2 54·7	– 58·4	– 61·8
S3	60·	58·6	56·2	54·4	56·0	59·8	61·6	69·4	70·2	75·8 56·6	73·1 53·	73·9 52·6	? 50·5	– 54·0	– 58·1
S4	–	58·6	58·4	55·2	56·4	58·2	59·4	69·6 55·8	71·9 54·2	73·2 49·2	74·2 46·7	72·6 48·0	? 48·5	– 53·4	– 56·1
S5		58·2	58·	53·6	55·5	55·8	56·4	65· 50·4	– 49·3	– 47·8	– 47·2	– 46·2	– 47·6	– 48·8	?
S6		–	–	?	47·2	47·9	48·0	44·8	46·0	44·4	42·5 31·	42·1 33·	43·3 33·	42·6	–
S7					?	41·	43·	41·	42·	38·	38·	36·4	37·1	?	–

* All entries have negative sign.

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Radial velocities of [Ne III] $\lambda 3868{\cdot}73$ Å

	E_7	E_6	E_5	E_4	E_3	E_2	E_1	EOW	W_1	W_2	W_3	W_4	W_5	W_6	W_7
N6	–	–	?	?	?	95·	95·	93·2	94·	–	–	87·	–	–	–
N5	–	99·2	?	?	92·	86·	84·	87·0	86·6	89·8	88·2	?	–	–	–
N4	84·6	87·4	87·6	85·4	85·8	83·4	77·6	77·2	82·4	84·6	86·6	79·8	85·2	?	–
N3	81·2 –	78·4 –	83·6 –	87·0 –	86·6 –	83·6 62·4	84·4 63·1	83·3 65·6	78·8	81·6	83·5	85·4	84·	80·	–
N2	74·9 –	75·4 –	76·5 –	78·6 –	77·0 –	81·2 58·7	87·9 66·1	74·6	76·1	79·1	79·6	80·5	77·6	75·4	–
N1	– 70·0	– 69·8	– 73·6	– 71·0	– 68·3	– 62·2	87·9 60·3	86·3 58·4	81·9 58·2	83·8 62·2	81·6 65·8	83·8 67·9	83·7 69·0	?	–
NOS	– 65·0	– 63·1	– 65·2	– 67·0	– 59·9	– 55·2	87· 52·8	82·4 53·8	79·5 49·6	74·0 48·7	72·2	82·0 62·2	79·1 59·8	75·0 58·0	66·
S1	– 61·6	– 58·2	– 59·8	– 63·5	75·3 57·6	78·4 50·3	79·5 47·1	80·2 42·6	77·4 42·2	79·5 66·5 42·9	83·0 65·6 –	81·2 61·2 –	74·9 56·2 –	71·6 57·5 –	– 59·6 –
S2	56·3	54·7	54·6	57·5	58·	69·0 47·0	74·4 43·1	73·0 41·	70·7 37·	68·6 42·	76·0 59·8 –	77·7 52·8 –	– 54·4 –	– 59·2 –	– 59·8 –
S3	52·	50·8	50·0	52·2	55·4	54·9	62·8 45·9	64·8 36·6	65·2 –	63·6 –	73· 53·4 –	76· 50·7 –	– 48·2 –	– 61·0 46·6 –	– 62·0 50·1 –
S4	49·	48·8	48·6	46·8	48·0	48·7	51·0	50·8	52·0	65·2 45·9	– 47·0	– 47·2	– 45·0	– 47·0 36·9	– 50·8 40·0
S5	–	47·	48·0	42·8	44·2	48·4	51·2	53·3	54·5	48·8	– 40·0	– 40·1	– 41·4	– 44·3	– 47·0
S6			–	42·	44·	45·4	47·8	46·8	– 39·0	– 36·4	– 35·2	– 35·7	– 36·6	– 36·2	?
S7						?	37·	38·	43·	?	33·	31·7	27·8	28·8	–

* Alletries have negative sign.

Table 3*

Radial velocities of [O II] λ3726·50 Å

	E_7	E_6	E_5	E_4	E_3	E_2	E_1	EOW	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8
N7																
N6																
N5	–	97·3	–	–	–	–	–	–	82·9	83·6	–	–	–	–	–	–
N4	88·9	90·9	–	–	–	–	70·1	72·8	79·2	88·7	88·9	91·4	–	–	–	–
N3	82·7	84·7	–	–	–	61·4	64·2	65·6	–	88·	89·8	89·6	–	–	–	–
N2	75·8	74·5	–	–	–	55·8	56·8	–	–	–	95·0	92·7	–	–	–	–
N1	71·0	69·0	–	–	–	51·5	57.	–	–	–	90·	90·9	–	–	–	–
NOS	66·1	64·1	–	–	46·4	47·	49·	–	–	88·	91·4	89·2	–	–	69·	68·0
S1	61·2	59·5	53·8	–	–	–	–	–	–	–	87·2	86·9	–	–	67·0	69·
S2	55·1	53·7	53·0	–	–	–	–	–	–	–	82.	–	–	–	62·6	64·8
S3	53·0	52·0	49·3	47·0	–	–	–	–	–	–	78·	–	–	–	56·2	57·2
S4	52·4	49·0	44·4	41·3	–	–	–	–	–	–	78·?	–	–	–	50·8	54·6
S5	–	50·	46·	45·8	44·6	49·8	49·8	–	–	–	–	–	–	45·8	44·4	–
S6	–	–	–	44·0	45·6	51·7	53·1	–	–	–	–	–	–	40·9	39·6	–
S7	–	–	–	–	–	–	–	–	–	–	–	–	26·1	30·2	–	–
S8	–	–	–	–	–	–	–	–	–	–	–	–	25·8	28·	–	–

* All entries have negative sign.

higher excitation lines. The Hβ image differs from the others mainly because the line widths are noticeably broader, indicating that the broadening is to some extent thermal in origin.

3. Interpretation

Although on a first impression the radial velocity field appears very complex, it is not difficult to discern a relatively simple trend in those points with single unblended lines. The most obvious feature is that the extreme radial velocities, around -100 and -25 km/sec, appear at the NE and SW corners of the nebula, the 'ansae' referred to by Curtis (1918). This situation is quite different from that found in the planetary nebulae with nearly circular symmetry (Wilson, 1950), where the extreme radial velocities are observed at the centre (two components). The whole set of radial velocities for the high-excitation lines, disregarding obvious blends, can be divided into two groups according to their magnitude. The largest velocities (in absolute value), together with the violet-displaced components at points where the lines appear double, very nearly define an area very nearly elliptical with axial ratio 7:4 and major axis in position angle 23°. In the same fashion, the smaller velocities, together with red-shifted components, define another ellipse, similar and parallel to the former. These two ellipses are partially overlapping in space but not in velocity. This general arrangement of the points according to their radial velocities is sketched in Figure 2, where the helical arms seen in the O^{++} images have been outlined. Along these

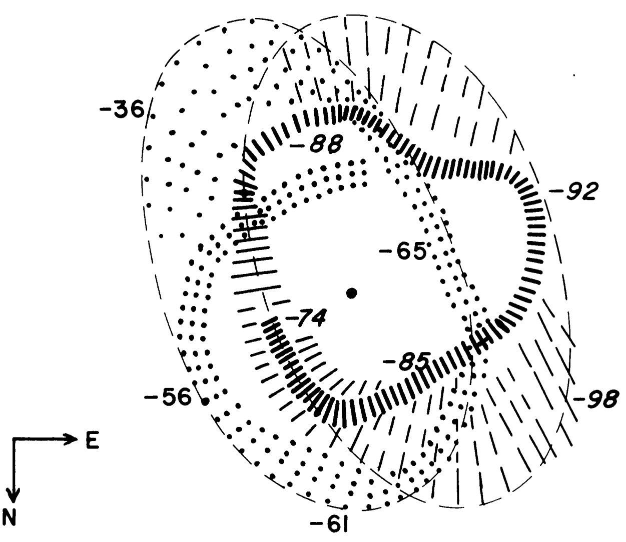

FIG. 2. *Regions of the planetary nebula NGC 6543 where the radial velocities of the* [O III] *lines are in absolute value small (dotted) and large (hatched). A few representative values of the velocities (km/sec) are entered for the approaching (italic figures) and receding (roman figures) loops.*

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structural features the radial velocities vary gradually, indicating continuity in their motion as well as in their density. It is noticed that the line joining the centres of the ellipses is nearly parallel to the minor axes of the ellipses and contains the exciting star at the centre. This fact, together with the similarity of the envelope ellipses, suggests that their true shape is nearly circular and that in space the nebular material is arranged on two helical surfaces with generatrix passing through the central star and forming an angle of $\cos^{-1}(4/7)=55°$ with the line of sight. A sketch of the suggested spatial arrangement of the nebular arms is shown in Figure 3. These arms are not, as

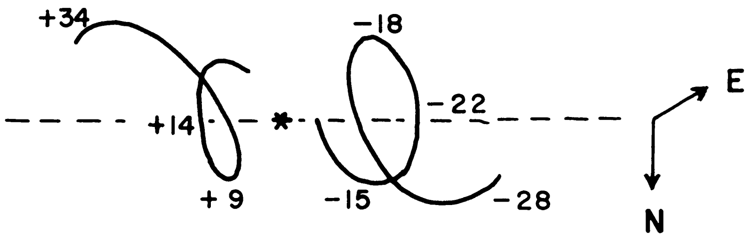

FIG. 3. *Side view perspective of NGC 6543. Only the densest parts of the nebular arms, as seen in the O^{++} radiation, are outlined. The representative radial velocities given in km/sec are relative to the central star and are uncorrected for foreshortening.*

depicted, isolated features, but rather are condensations on helical sheets which contain sufficient matter to shield the outer regions from the ultraviolet radiation of the central star, as required by the observed ionization stratification.

The relative radial velocity between the inner parts of the approaching and receding loops (from the star) is approximately $V_0=24$ km/sec, and if it is the result of a uniform symmetrical expansion from the central star, the time T since the expansion began is obtained from the distance D of the nebula and the angular separation (5″.5) between the centre of the two ellipses expressed in radians. If the distance is 1000 parsecs (O'Dell, 1963), the lifetime of the nebula is thus 1000 years, about 1 order of magnitude shorter than that generally considered 'typical' for a planetary nebula (Abell and Goldreich, 1966). It should be noticed that the dimensions in cross-section of the nebular arms are at present a few seconds of arc. Since the velocity of sound in the nebula is around 20 km/sec, the thermal diffusion of the arms in 1000 years would not be sufficient to make them lose their identity. That is to say, if the ejection took place from two localized regions diametrically opposite to each other on the surface of the star parent to the present nucleus, and, thus, was confined to a tube of diameter small compared to its length, not enough time has elapsed for the arms to diffuse completely. In fact, this argument can be inverted to fix the time since ejection and hence derive the distance, once it is supposed that no *ad hoc* forces (e.g. of a magnetic nature) are stabilizing the nebular arms. It should be pointed out that to stabilize the arms at present magnetically, a field strength of the order of 5×10^{-3} Oersted is required. This would imply an impossibly large field in the early phases of the expansion. Under the plausible assumption, then, that the loops will continue their present axial expansion and thermal diffusion uniformly, one can see that when the 'typical' lifetime of a planetary has elapsed the helical arms seen today in NGC 6543 will have disappeared and the nebula will be a low surface brightness amorphous planetary.

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DISCUSSION

Liller: We have measured the angular radial motion for several filaments in NGC 6543 on 60-inch Cassegrain plates. The mean motion we have derived is $+0''.5 \pm 0''.1$ of arc per century.

Terzian: I would like to mention that the observed optically thin radio flux of NGC 6543 is 0·9 flux units and that predicted from its Hβ flux is 1·6 flux units. This large difference probably is not due to observational errors.