

Part V: Kinematic Structure of Gaseous Envelopes

Internal Kinematics of the Planetary Nebulae

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1. SPECTRA

A COMMON form of planetary nebula consists of a high temperature nuclear star surrounded by an ovoid or ellipsoidal shell of gas which has originated in some manner in the nucleus. The radiation from the nebula consists of the ordinary spectral lines and continua of hydrogen and helium plus the so-called forbidden lines of atoms and ions of oxygen, nitrogen, neon, argon, etc. It has become clear that, as in other cosmic bodies, the bulk of the nebula consists of hydrogen and helium, and the remainder of the chemical elements occur only as a slight admixture of impurities. For instance, recent data by Aller and Minkowski¹ lead to relative numbers of atoms of various chemical species in a particular nebula (NGC 7027) as follows (oxygen arbitrarily taken as 10^4):

H	1.2×10^7	S	1.3×10^3
He	1×10^6	Cl	1.2×10^2
N	5×10^3	A	2.4×10^3
O	10^4	K	18
F	5	Ca	16
Ne	1.5×10^3		

These abundance data explain in a general way the nature of the nebular spectra. Hydrogen and helium atoms are so numerous that they absorb nearly all of the ultraviolet radiation of the nucleus and, in so doing, are ionized. Subsequent processes of recombination and cascading of electrons from higher to lower atomic levels yield the complete spectra of hydrogen and helium. Thus the hydrogen lines will be emitted in any portion of a nebula where hydrogen is present and where the ultraviolet nuclear energy has not been previously removed by absorption.

The same statement may be made concerning helium, but with a slight modification. Helium has two outer electrons and in the inner parts of the nebular shell there may be enough ultraviolet energy to remove them both, whereas farther out, where the radiation has been depleted, the remaining quanta may be adequate to remove only one of them. Therefore, complete spectra of either HeII or HeI will be emitted by any

portion of the nebula where He is present and where the ultraviolet nuclear radiation is sufficient for double or single ionization, respectively.

For the other chemical elements in the nebulae the situation is quite different. Not only are the most plentiful of them at least a thousand times less abundant than hydrogen, but also their term structures are such that their recombination spectra in the observable region consist of large numbers of lines none of which are strong. The result is that virtually nothing is seen of the normal recombination spectra aside from those of hydrogen and helium. However, many of these atoms and ions have metastable energy levels only two or three volts above their ground states. Normally, an electron occupying an excited state in an atom will spontaneously jump to a lower level, thereby emitting a quantum, in a time of order of 10^{-8} sec. But, because such transitions are forbidden by certain selection rules, an electron in a metastable level may remain there for seconds or even hours before spontaneously jumping to the ground state. In the nebulae there are vast numbers of free electrons, produced by ionization of the abundant hydrogen and helium. These electrons have average kinetic energies of a few volts, and by collision excite the other atoms and ions to their metastable levels. Thereafter, under the conditions of extreme low density prevailing in the nebulae, there is plenty of time for the excited particles to wait unperturbed until spontaneous jumps to the ground state, or to intermediate states, produce quanta of the forbidden lines.

Thus a forbidden line of a given ion will be produced in those nebular regions where the particular ion is relatively plentiful and where there is also an ample supply of free electrons. Ions requiring high excitation, such as NeV for instance, would be expected in the inner portions of nebular shells and that is indeed where they occur. Low excitation particles like OI are expected, and found, in the outer parts. Indeed, there may be plenty of OI outside the visible boundary of a shell, but since hydrogen is no longer ionized there, free electrons do not exist to excite the forbidden lines into visibility. In between the regions of NeV and of

¹ L. H. Aller and R. Minkowski, *Astrophys. J.* **124**, 110 (1956).

OI there should exist a steady outward decrease of ionization requirements.

2. OBSERVATIONS

Internal motions in the planetaries can be studied only by means of radial velocities as revealed by a spectrograph. Angular motions across the line of sight are far too small to be useful over the time intervals available to us thus far. Since the bright planetaries are small objects, with diameters of the order of 10 to 20 sec of arc, they can be adequately resolved only with large telescopes of long effective focal length. Moreover, the spectrograph should have fairly high dispersion and high speed, and should be transparent over a long range of wavelength. All of these requirements are met by modern Coudé spectrographs, equipped with gratings and Schmidt cameras, and used in conjunction with a large reflector. An image rotator is also a great convenience, and for some work a necessity, since without it the image of an extended object rotates on the slit during an exposure at the rate of 15° per hour.

Such equipment may be used in the conventional manner by placing the image of a planetary on the slit, in any desired orientation, and exposing for a suitable length of time. On the plate one then gets a record, in the various lines, of the motion toward or away from the observer of the corresponding particles which are in that cross section through the nebula where the slit crosses the image.

If the slit is removed, and some means of guiding provided, slitless photographs of the nebulae may be obtained. In these, each monochromatic radiation forms its own picture thus revealing the distribution of the corresponding particles in the nebula.

Finally, the single slit may be replaced by a series of slits of equal width and fixed separation such that a number of them lie across the nebular image. With this "multislit" arrangement kinematic information is secured simultaneously for all sections through the nebula where one of the slits crosses the image.

3. INTERNAL KINEMATICS OF THE PLANETARIES

We have seen that in a nebular shell surrounding a hot star the level of ionization should decrease from the inside outwards, but that hydrogen emission should take place throughout the entire visible shell. Moreover, because of the large preponderance of hydrogen and helium atoms, the others, which produce the various forbidden lines, cannot have independent motions of any consequence, but must simply be carried along with the hydrogen and helium, like twigs floating with the current of a river. Thus the hydrogen lines should give the kinematic picture of the shell as a whole. The forbidden lines, however, will serve as markers which enable us to determine the H-He motions at intermediate points within the shell.

In general, the spectrum lines from an object of the type we have been considering are double near the center of the apparent disk, and then the components approach each other and coalesce at the edges. The only reasonable interpretation is that the shell is expanding outward from the nucleus. The violet components of the double lines thus represent emission from the near side of the nebula and the red components originate in the far side.

If there is a velocity gradient within the shell, the components of the hydrogen lines should be broadened correspondingly since all of the velocities within the shell should be represented in the hydrogen emission. In addition, since the nebular temperatures are probably of the order of 10 000°, thermal broadening of the hydrogen lines should be appreciable. It is observed that the components of the hydrogen lines are indeed widened noticeably even with a dispersion of 10 Å/mm. At present there is no information as to how much of the effect is due to temperature and how much to velocity gradients. The two contributions can probably be disentangled by making appropriate high dispersion observations at the center of a nebula and at the edge. The difference between these should be the part of the widening which is due to the velocity gradient.

Apart from hydrogen, and possibly helium, the widths of the components of the other nebular lines seem to be about equal, with rare exceptions, to the limit set by the plate resolving power. For the dispersion used in most of the work this quantity corresponds to the order of 10 km/sec. Since the expansion velocities are usually something like two to three times as great, one may conclude that any turbulent velocities in the planetaries are considerably less than the flow velocity, and also that within the zones where the individual forbidden lines are produced the velocity differences due to a gradient are not large.

The foregoing remarks are of particular interest because in many of the ovoid nebulae the surface brightness of the disk is far from smooth and uniform. Many have a decidedly mottled appearance with rather large and numerous intensity fluctuations over the surface. Presumably, since all of the nebular emissions vary as the square of the gas density, these intensity fluctuations reveal corresponding density variations within the shell. Nevertheless, again with some rare exceptions, there are no measurable velocity fluctuations corresponding to those of surface brightness. Any irregular motions associated with the density fluctuations must be relatively small. In this context a planetary nebula reminds one of a rubber balloon which is being slowly inflated and on the surface of which is painted a pattern of brighter and darker areas, all necessarily moving outward at the same rate.

In spite of the lack of evidence for irregular internal notions, internal velocity differences are quite common and sometimes surprisingly large. They are revealed by measures of the separations of the components of lines

of different origin. These component separations are, of course, equal to twice the expansion velocities of the emitting particles.

Measures of single slit spectrograms of most of the bright planetaries reveal a general relationship between the ionization potentials of the various ions and their expansion velocities. This is in the sense that for the higher ionization potentials the expansion velocity is smaller than for hydrogen, while the reverse is true for the particles with low ionization potentials. Physically, this means that the inner parts of the visible shells are expanding slower, the outer parts faster, than the average. For example the results for NGC 7662 are as follows:

Ion	H	[OII]	[OIII]	[NeIII]	HeII	[NeV]
I.P. (v)	13.5	13.6	35.00	40.9	54.2	96
ΔV (km/sec)	52	58	53	52	46	39

NGC 7662 is a high excitation object (NeV is present) and in some of the others of the same kind even more extreme velocity differences are found. In a number of them the [NeV] lines are actually single, that is, they show no measurable expansion velocity at all.

The effect is not, however, restricted to the high excitation nebulae. IC 418 is a relatively low excitation object and the measures of a number of spectrograms yield these values.

Ion	[OI]	MgI	[SII]	[OII]	[NII]	H	[OIII]	[NeIII]
I.P. (v)	0.0	0.0	10.3	13.6	14.5	13.5	35.0	40.9
ΔV (km/sec)	47	39	34	21	23	0	0	0

In this nebula the hydrogen lines, though single, are broad, but the lines of [OIII] and [NeIII] remain sharp and single even with dispersion of about 2 Å/mm.

In every instance where differences in image size on slitless spectrograms are perceptible, it is found that the highest excitation particles are located in the inner parts of the visible shells and the low excitation particles in the outer parts. Therefore the velocity measures are probably to be interpreted thus: The nebular shells are disintegrating under the influence of internal pressure; matter near the inner boundary is being forced inwards while that near the outer boundary is being ejected outwards. Undoubtedly the disintegrating internal pressure is due to the accumulation of energy from the nucleus in the form of quanta of Lyman- α . One of these quanta is the end product of every ionization of a hydrogen atom. However, there is one apparent difficulty here which can be easily resolved. Milne² has shown that for diffuse nebular radiation originating in a spherical shell, the inward flux at a point on the inner boundary is equal to the outward flux due to the radiation from all other parts of the inner surface, and this must be true of the Lyman- α radiation. This difficulty can be avoided if the velocity on the inner boundary is not exactly zero. In this case the quanta arriving at a given point from most of the inner surface will not have the proper wavelength to be absorbed and

² E. A. Milne, *Z. Astrophys.* 1, 98 (1930).

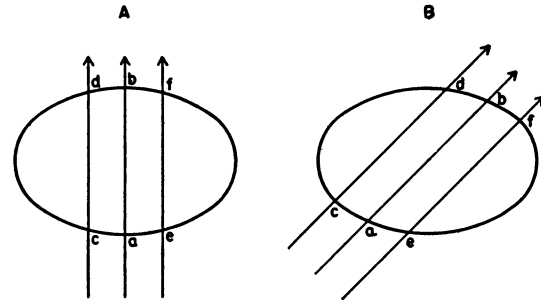


FIG. 1. Schematic representation of ellipsoidal nebula viewed at right angles to major axis (A) and at 45° to major axis (B).

hence can pass through without influencing the inward flow of material, and can even escape from the nebula altogether. If, however, the condition of zero velocity is attained all over the inner boundary, then Milne's theorem would apparently call a halt to further inward ejection.

4. GEOMETRIC-KINEMATIC CONSIDERATIONS

Nebulae exist which appear very irregular indeed and one has no idea how they have developed into their present forms. But many have a roughly ellipsoidal appearance and it is not unreasonable to ask whether it is possible to account for them. By far the simplest way of doing so is merely to suppose that in the original ejection process, on or near the surface of the nuclear star, the material was ejected with velocities which were a function of the direction of motion. If the velocities were greater in the equatorial regions than near the poles (or vice versa) and if the material then moved outward in straight lines and maintained its original velocity distribution, the result, after a while, would be a shell of more or less ellipsoidal shape. Out of a number of ellipsoidal nebulae oriented at random in space, an occasional one will be viewed nearly at right angles to its major axis and thus seem more elongated

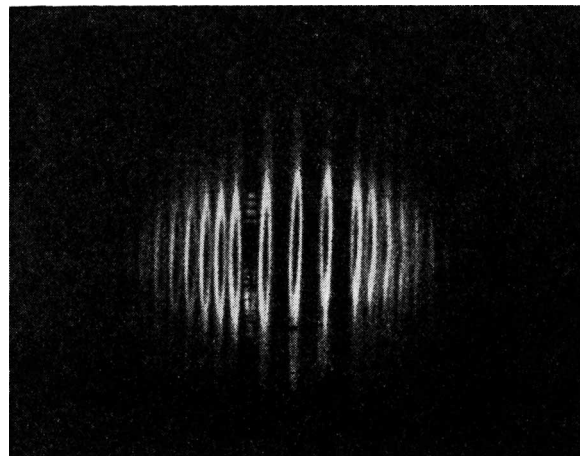


FIG. 2. Multislit images of $\lambda 3868$ [NeIII] in NGC 7009. Note approximate symmetry of lines on either side of center, also slow decrease in separations of lines away from center.

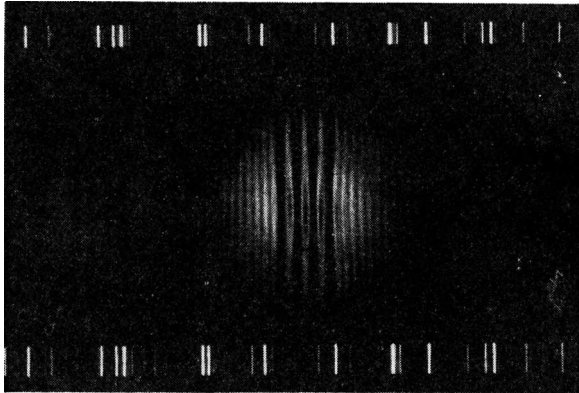


FIG. 3. Multislit images of $\lambda 3868$ [NeIII] in NGC 7662. Note marked asymmetry (and its reversal) on the two sides of the symmetrical central image.

than most. Also, an occasional one will be seen almost along its major axis and will appear nearly round. But most of them will be viewed in some intermediate position and will appear as ellipsoids of moderate elongation.

Now consider the schematic representation in Fig. 1 of two nebulae of the type just discussed. In *A* the line of sight is perpendicular to the true major axis of the nebula while in *B* the nebula is viewed at 45° to its true major axis. In both nebulae the matter in the shell at any point is supposed to be moving out from the nucleus in the direction of the radius vector to the point in question. The three arrows represent the lines of sight for three slits of a multislit, the central one of which is placed on the nucleus.

In *A* the angle between the radius vector and the lines of sight is the same at *c* and *e* as it is at *d* and *f*, and the radius vectors to *c*, *d*, *e*, and *f* are all equal. Thus one would expect to find a symmetrically doubled line for the central slit, corresponding to *a* and *b*, and

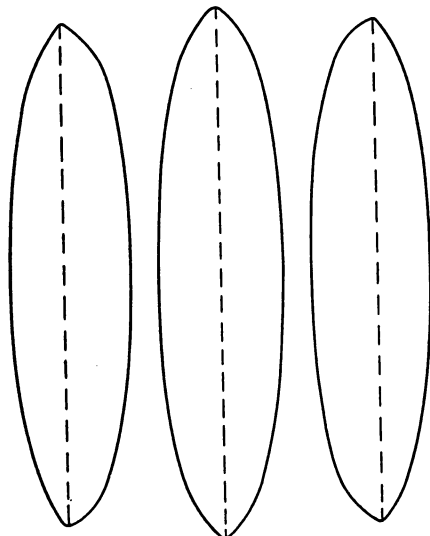


FIG. 4. Calculated lines. Compare with Fig. 3.

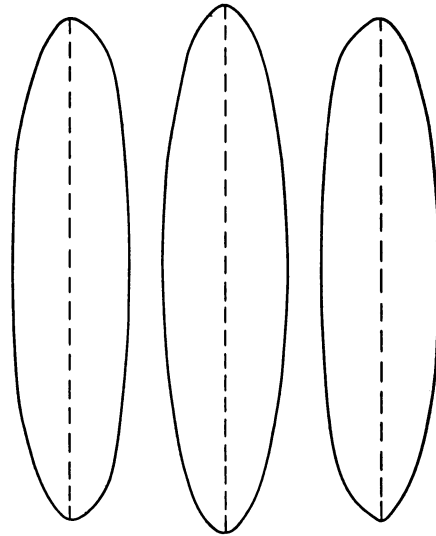


FIG. 5. Calculated lines, velocity constant over shell. Note that asymmetry is very slight.

flanking it on each side should also be symmetrically doubled lines from *cd* and *ef*. The situation is quite different for case *B*. Here the radial velocity at *a* is equal and opposite to that at *b* so the central line should be symmetrical. But the radial velocity at *c* will have the same numerical value as that at *f* and the velocities at *e* and *d* will also have the same magnitudes. Thus the symmetrical central line should be flanked by unsymmetrical ones and the asymmetry should be equal and opposite on the two sides of the center. Do we find such effects in real nebulae? The answer appears to be yes.

Among the bright ellipsoidal nebulae NGC 7009 is the most elongated, with apparent major and minor axes in approximately a 3:2 ratio. It is probable that this is nearly equal to the true axis ratio and that we are viewing this nebula from a direction nearly at right



FIG. 6. Calculated line for model used for Fig. 4, slit on apparent major axis.

FIG. 7. Same as Fig. 6 except velocity constant over the shell.



angles to its major axis. Figure 2 shows a multislit image of the [NeIII] radiation, $\lambda 3869$. Note, first, that not only is the central slit image symmetrical in character, but that the ones on either side are also very nearly symmetrical, as would be expected from case *A* of Fig. 1. NGC 7662 is a bright nebula with considerably less apparent ellipticity than NGC 7009. A multislit image of the same [NeIII] radiation in this nebula is shown in Fig. 3. Here the central slit image is again symmetrical, but the ones on either side are decidedly unsymmetrical and in the opposite sense on the two sides of the central image. This is very suggestive of case *B* in Fig. 1.

We can proceed a step farther by assuming a simple model and calculating the lines to be expected from it. Let us take as a model an ellipsoid of revolution whose major and minor axes are in the ratio 3:2, and imagine

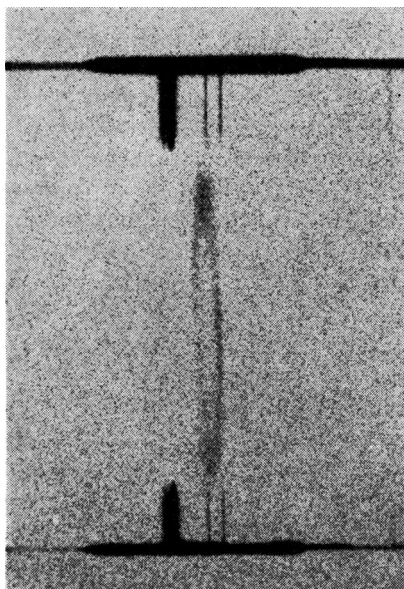


FIG. 8. Observed N2 line in NGC 7662, slit on major axis.

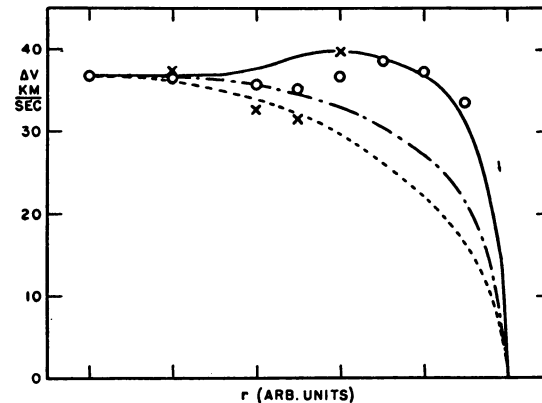


FIG. 9. Measured line separations as function of distance from center (NGC 7009), compared with those calculated.

that it is being viewed at an angle of 45° to the major axis. We assume further that the expansion velocity at any point on the shell is proportional to the length of the radius vector to the point. Under these circumstances the three central line images are as shown in Fig. 4, where the resemblance to the observed lines of Fig. 3 is quite noticeable. For comparison, Fig. 5 shows the result when the velocity of expansion is taken to be constant over the shell, the other parameters remaining the same. With the velocity constant, the asymmetry of the images on either side of the central one almost disappears.

If the spectrograph slit is placed along the major axis of our hypothetical nebula, the resulting line is as shown in Fig. 6. Again, if it be assumed that the velocity is constant over the shell but the other circumstances are unchanged, we get the result of Fig. 7. The N2 line as observed in NGC 7662 (Fig. 8) bears a strong resemblance to the calculated line of Fig. 6.

Lastly, returning to Fig. 2, note how the separations of the components in the successive line images diminish very slowly outward from the center in NGC 7009. In Fig. 9 are shown the results of measures of this image, the circles and crosses referring to the two sides of the nebula. For comparison, the solid curve is computed with the assumption that the velocity is everywhere proportional to the radius vector, and the dash-dot curve that it is constant over the nebula. The dotted curve is the result for a spherical nebula with radius equal to the semimajor axis.

Thus three different comparisons with observation tend to support the simple explanation of the ellipsoidal nebulae given at the beginning of this section. It is probable therefore that the ellipsoidal nebulae have been such from their beginning and that their present forms reflect the angular distributions of velocity with which the original ejections of matter took place from the nuclei. Since then the material in the shells has been moving outward in straight lines, but the shells are subject to disintegration both inward and outward because of internal Lyman- α pressure.