EMISSION-LINE PROFILES IN PLANETARY NEBULAE

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This research was undertaken with the idea of measuring as accurately as possible the internal-velocity distribution in planetary nebulae, in order to compare the observational measurements with hydrodynamical models of expanding nebulae. Much of the work was done in collaboration with J. S. Miller and D.W. Weedman. All the observational data were obtained photographically with the Coudé spectrograph of the 100-inch telescope at Mt. Wilson, using an image rotator, a 900 line/mm grating, and an $F/5{\cdot}2$ camera, giving a dispersion of about 4 Å/mm in the blue and about 6 Å/mm in the red. The measured velocity resolution is approximately 5–6 km/sec. The data for five nebulae have been published (Osterbrock *et al.*, 1966) while data for three more, NGC 2392, NGC 3242, and IC 418 are discussed here for the first time.

All the spectrograms I will discuss here were taken with the slit through the central star, and all the tracings I will discuss were made at the centre of the nebular image, so they refer to the distribution in radial velocity of material along the line of sight through the centre of the nebula. The measurements published in the first paper showed that the nebular emission lines are not only double, as is well known from the work of Wilson (1948), but also have widths which vary systematically with atomic weight in the sense that the lightest element, H, has the widest lines, and the heaviest elements (O, N) have the sharpest lines. The widths are partly due to thermal Doppler broadening, but in addition there must be considerable range in mass motion, for the profiles of the lines and their widths cannot be interpreted as due to thermal broadening alone. In typical planetaries such as NGC 7662 the observations show that along a line through the centre of the nebula there is material with velocity ranging between approximately $+10$ and $+40$ km/sec, and also material with velocity ranging between -10 and -40 km/sec. This range of velocity is probably due to the outward gradient of expansion velocity discovered by Wilson (1948) from the observed correlation between ionization potential and measured velocity of expansion, though from the tracings of the spectrograms taken at the centre of the nebula alone it is impossible to separate this effect from any possible turbulent velocity that might be present.

The new measurements show that NGC 3242 is a typical nebula with double lines, and I will not discuss it further here. IC 418 is interesting in that though the [N II] lines are double, the [O III] lines are single (Figure 1). This is due to the fact that O^{++} is concentrated to the centre of the nebula where the expansion velocity is lower, while N^{+} occurs in the outer part of the nebula where the expansion velocity is larger.

Osterbrock and O'Dell (eds.), Planetary Nebulae, 267–269. © *I.A.U.*

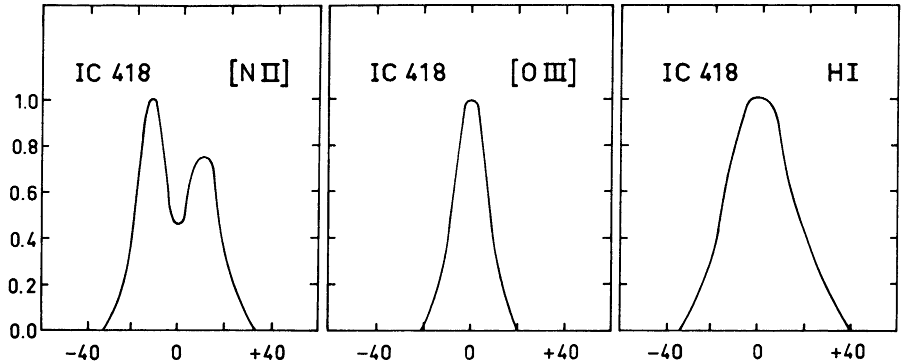

FIG. 1. *Measured line profiles of* [N II] *(average of 4 separate exposures),* [O III] *(average of 6), and H* I *(average of 5) at the centre of IC 418.*

The observed H I lines are also single, partly as a result of the fact that H has a higher thermal Doppler width, and partly due to the fact that the H lines are formed throughout the nebula. At the present time we are carrying out calculations to see if the H I profile can be quantitatively understood on the basis of velocity distributions obtained from the [N II] and [O III] lines.

The most interesting emission lines are those observed in NGC 2392, the planetary nebula with the largest expansion velocity measured by Wilson (1948). The [O III] images reproduced in Figure 2 show the complications very well. In the bright ring

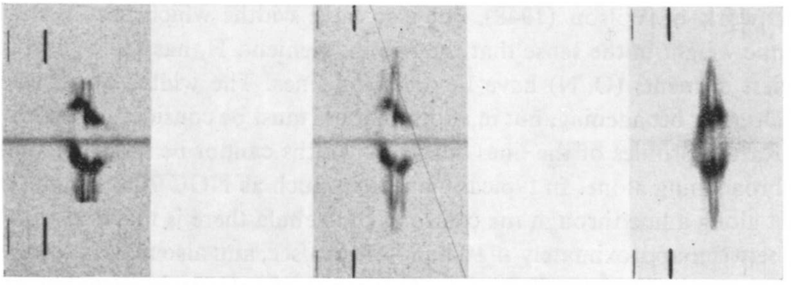

FIG. 2. ***Reproductions of*** [O III] ***λ5007 emission line of NGC 2392. Left and centre are two different exposures with slit oriented North–South through centre of nebula; right, slit East–West through centre.***

there is a range in radial velocity of over 100 km per second. The outer structure seems to belong to a different kinematic system from the inner structure, as is also the case in NGC 7662. The spectrum of NGC 2392 taken with the slit East–West shows particularly clearly that in addition to the system expanding with approximately 50 km/sec radial velocity at the centre of this nebula, there is another component with approximately 0 km/sec radial velocity, perhaps connected with the outer structure of this nebula. The schematized theoretical picture of a spherically symmetrically expanding nebula is evidently far too drastic a simplification to apply to NGC 2392.

Further analysis of the spectrograms all along the slit length (that is to say all along a line that projected on the sky goes through the centre of the nebula and that therefore is the trace of a plane through the centre of the nebula) by Weedman tends to confirm the picture of Wilson (1958) that many planetary nebulae can be understood as prolate spheroids with axial ratio approximately 3:2. Measurements of the line profiles at the ends of the slit image (that is looking tangentially through the nebula) show that the turbulence is small, and that any turbulent velocity that does exist is less than 5 km/sec. In NGC 7009, examination of the slit images show that there are many abrupt near-discontinuities in velocity (of the order of 3–5 km/sec), that velocity changes are correlated with density changes, and that there is a symmetry to the patchy inhomogeneous structure of the nebula, in the sense that regions of high density tend to be diametrically opposite regions of high density, and regions of low density tend to be diametrically opposite other regions of low density. Theoretical work on the interpretation of these measured line profiles is continuing.

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References

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DISCUSSION

Liller: Does NGC 2392 appear to have an outward velocity proportional to radius, or constant with radius as Wilson's data and our data seem to indicate?

Osterbrock: We have not measured the plates of this nebula yet, so I cannot answer the question.

Münch: On the basis of your material can you say definitely, for one selected planetary nebula at least, whether the microturbulence is less than the thermal root-mean-square velocity? This point is important, because the galactic H II regions have microturbulence that is just transonic, and therefore there must be a fundamental difference in this respect between the two classes of objects.

Osterbrock: Weedman's measurements show that in at least two planetaries, NGC 7009 and NGC 7662, if there is any microturbulence its root-mean-square velocity is less than 5 km/sec.

O'Dell: Can the [O I] λ6300 line profile be measured? This would be especially interesting as it should arise in the outermost regions of the nebula.

Osterbrock: No, it was too faint to be photographed at this high dispersion with the equipment I had. An image tube would help a lot.

Aller: By combining multislit spectra and monochromatic isophotal contours, it is possible to get information not only on the velocity pattern in a planetary nebula, but also on the three-dimensional distribution of the emitting matter. Such observations have been made for NGC 7662, using multislit spectrograms taken by Wilson. The bright inner shell contains a number of intensity fluctuations, indicating knots and condensations, as one would expect. The illustration is published in *Progress in Fluid Dynamics*, edited by Temple and Seeger.