EXPANSION VELOCITIES AND CHARACTERISTICS OF GALACTIC PLANETARY NEBULAE

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ABSTRACT. An up-to-date account of expansion data and their interpretation is provided.- The importance of spatiokinematical models is underlined; bipolar outflows appear to be characteristic of very young objects and prolate spheroids (including toroids and rings) seem to be a useful approximation for many PN.- High-velocity features are much more frequent than previously assumed.- Expansion velocities vs. linear radii diagrams for [OIII], HI, and [NII], based on a new catalogue show a broad, rather homogeneous distribution and thus are of limited value for studies of the dynamical evolution or formation mechanisms of PN - future investigations of these relations should be pursued separately for groups of PN with similar physical properties; a difference in the kinematical properties of B and C nebulae could, however, be confirmed.- Several recommendations for work in this area are added.

1. INTRODUCTION

A knowledge of expansion in PN is the basis for an understanding of the kinematical and dynamical processes in these objects. Expansion velocities and their correlation with various nebular and stellar parameters are, generally, of great value with regard to the conceptions on the evolution of the nebulae and their central stars.

Campell and Moore (1918) were the first who noticed the double, bowed appearance of emission lines. The first interpretation as expansion was given by Wilson (1950); he also noticed that the smallest expansion velocities (V_{exp}) are observed for the highest ionization degrees, and the largest V_{exp} for the lowest ones; also, V_{exp} was found to increase with distance from the nebular center. Weedman (1968), by deriving simple spatiokinematical models, supposed most PN to be prolate spheroids (i.e., an ellipse

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rotated about its major axis). The earliest fully hydrodynamical models of expanding nebulae were calculated by Mathews (1966).

In recent years,an enormous increase of expansion data took place, by use of long slit high-dispersion coudé and echelle spectrographs, and single aperture Fabry-Perot interferometers.

Within the last 5 years, with regard to V_{exp}, the by far most data were obtained by Sabbadin and his collaborators (19 papers - for the majority of references see, e.g., Sabbadin 1984), on compact and extended PN. Numerous (i.e., >10) PN were also observed by: Robinson, Reay, Atherton (1982; mostly compact PN); Welty (1983; mostly extended PN); Gieseking, Hippelein, Weinberger (1986; very extended PN); Mendez et al. (1987; mostly compact PN); Hippelein, Weinberger (1987; very extended PN); Chu and Jacoby (1987; multiple shell PN).

A catalogue of all V_{exp} was presented by Sabbadin (1984). A new catalogue of V_{exp}, complete up to July 1987, was prepared by Weinberger (1987).

As to spatiokinematical models, most of them were derived by Sabbadin and his co-workers (for most references see, e.g., Sabbadin 1984). Further references are given below and a complete list of references can be found in Weinberger's catalogue.

Recent interpretations of internal motions in context with nebular and/or stellar evolution are contained in: Sabbadin et al. (1984); Phillips (1984); Okorokov et al. (1985); Volk and Kwok (1985; Schmidt-Voigt and Köppen (1987).

In this review the emphasis is laid on spatiokinematical models and their common properties, PN with high-velocity features, the new compilation of expansion velocities and its various implications, and some cautionary remarks.

Neither expansion characteristics of the shells of multiple shell PN nor those of extragalactic PN will be discussed, since they are parts of other reviews in this symposium (Chu 1987, and Barlow 1987, respectively).

2. SPATIOKINEMATICAL MODELS

Spatiokinematical models are of crucial importance for the understanding of the 3-dimensional form and the kinematics and dynamics of PN. One of the main advantages is the possibility to derive true (=deprojected) expansion velocities, due to the non-sphericity of the vast majority of PN. The construction of detailed, reliable models is, however, rather time consuming and difficult and, as a consequence, only few reliable spatiokinematical models exist.

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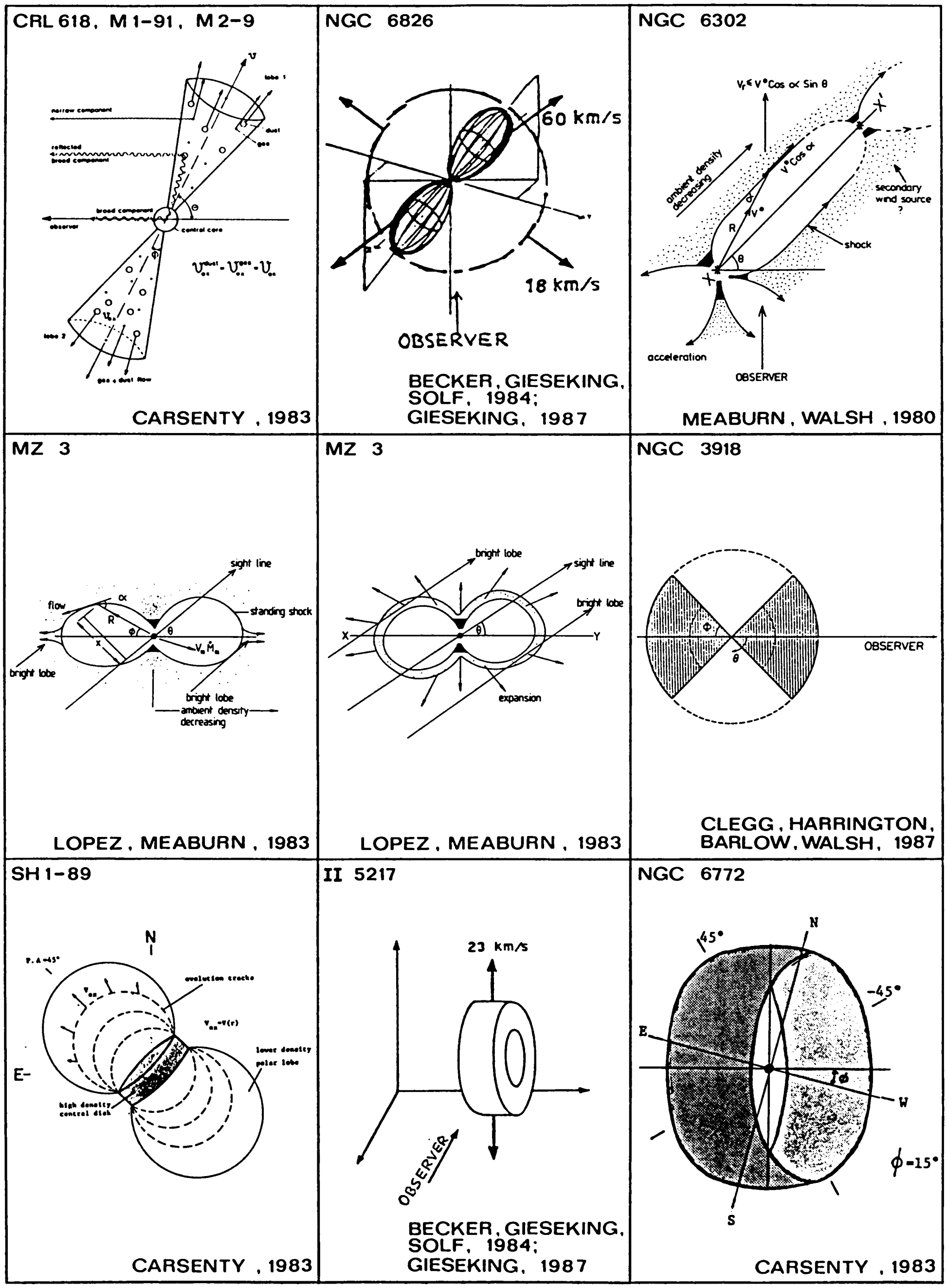

Figure 1. Sketches of typical spatiokinematical models; the drawings shown here comprise 1/3 of all published sketches.

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At present, spatiokinematical models for 42 PN are known; for a few objects, more than one model exists. In the literature, altogether 27 sketches of such models (comprising 19 PN) could be found. In Fig. 1 one third of these drawings, a representative sample, is shown. From the 27 sketches and the residual descriptions on all 42 PN as taken from the literature, we draw the following, preliminary and necessarily rough conclusions (by taking the evolutionary status of the PN into account):

Very young PN consist of compact (disklike/toroidal) central nebulae and distinct bipolar fast outflows; young and middle-aged PN show bright, thick toroids or rings and faint bipolar outflows, i.e., they are prolate (often truncated) spheroids, expanding more rapid along their major axes. For old PN too few models exist to form analogous opinions about them. In addition, a rich variety of faint (usually outer) features (ansae, filaments, halos etc.) with heterogeneous expansion characteristics exist. High dispersion spectra also show that numerous condensations are quite typical.

One may surmise that an increase of detailed spatiokinematical models will lead to a modification of the above tentative conclusions, e.g., by introducing new conceptions like that of Recillas-Cruz and Pismis (1984) on NGC 650-1 for some other objects.

3. HIGH-VELOCITY FEATURES

We will first shortly discuss the most spectacular high-velocity features and then try to find some common properties.

NGC 6302: Meaburn and Walsh (1980a), and Barral et al. (1982) report on a central disk and a wind produced ionized elongated main cavity and additional cavities. The ionized walls of the main cavity flow at ca. 300 km/sec away from the dense core. In the core region, the [NeV] 3426Å line is observed to be 800 km/sec in extent and is interpreted as direct emission from radiatively ionized gas, provided the distance is not much larger than D = 150 pc.

Mz-3: This object appears to be spatiokinematically similar to NGC 6302. The Hα line is 2460 km/sec broad and is observed in the core region; it is interpreted as produced by electron-scattering, provided D ≈ 1 kpc (Lopez and Meaburn 1983).

M2-9: Swings and Andrillat (1979) and Walsh (1981) report on a very broad Hα line stemming from the core region. According to the former authors, its extent is 1000 km/sec.

He2-111: a range in velocity of about 400 km/sec between two parts near to the nebular borders in the southeast and northwest is reported. If the nebula is a cylindrical shell

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(the major axis appears to be close to the plane of the sky), then the true outward velocity must be appreciably larger (Webster 1978).

NGC 2392: Besides high-velocity components, the main body of this pole-on object has the largest V_{exp} (true V_{exp} 53 - 93 km/sec) of all PN. O'Dell and Ball (1985) found a high-velocity stream with a true V_{exp}([OIII]) = 190 km/sec away from the center. Gieseking, Becker and Solf (1985) also detected a jetlike multiknot bipolar mass flow starting from the center, with a true V_{exp}([NII]) = 200 km/sec. These features are best reproduced in the annual report 1986 of the Max-Planck-Institut für Astronomie, in Mitt. Astron. Ges. 69, p. 166.

NGC 6537: Becker and Solf (1983) suppose the nebular center to be a compact, possibly ringlike structure; in addition, a bipolar flow appears to be present: hollow, elongated shells expand away from the center with true V_{exp}([NII]) $\approx$ 230 km/sec.

NGC 6543: A bipolar jet with a true V_{exp}([NII]) $\lesssim$ 50 km/sec was discovered by Solf (for a reproduction see annual report 1986 of the Max-Planck-Institut für Astronomie, in Mitt. Astron. Ges. 69, p. 166).

NGC 6826: Becker, Gieseking and Solf (1984) suppose this object to consist of 3 main components, one being an "hourglass" with a true V_{exp}([NII]) of ca. 60 km/sec along the major axis.

NGC 7293: According to Meaburn and Walsh (1980b), a small (15") region projected near the inner rim of the bright helix expands with V_{exp}([OIII]) = +66 km/sec with respect to the mean velocity of the PN. Meaburn and White (1982) noted that this small region is a part of a much larger very faint feature. Walsh and Meaburn (1987) found a filament, 11' west of center, that moves with V_{exp}([NII]) = +50 km/sec with respect to the mean velocity; it may be part of a radially expanding ellipsoidal shell.

He2-36: Feibelman (1985) discussed a possible high-velocity jet with a true V_{exp} of ca. 600 km/sec, but later Lutz et al. (1986) found no evidence for the jet.

Provided that the results on high-velocitiy features are representative, we conclude:
1) the frequency of such features is much larger than previously assumed; 2) young and/or proto-PN (particularly "butterflies") show distinct high-velocity flows in their lobes and very broad line components in their centers; 3) in evolved PN high-velocity jets, knots, filaments etc. can be present, but their number or other details are largely unknown; 4) the physical nature of high-velocity features is poorly or not at all understood (anyway, the stellar winds appear to be of importance).

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4. THE NEW V_{EXP} CATALOGUE AND SOME CONSEQUENCES

Up to now, compilations of V_{exp} in PN were mainly used for V_{exp}([OIII]) vs. linear radii (r) diagrams, as basis for understanding the dynamical evolution and formation mechanisms of these nebulae.

The most recent catalogue of expansion velocities in PN was compiled by Sabbadin (1984) and contains 165 objects. The present catalogue (Weinberger 1987) contains expansion velocities observed in 237 planetaries, as derived from about 100 papers. Most linear radii in the new catalogue are based on an enlarged set of "reliable" (i.e., ≤±50%) distances, with the enlargement to a large part due to distances taken from Mendez et al. (1987). In case of several nebular components, the data listed refer to the main, usually centrally located nebula and generally are the expansion velocities at or near the centers in extended objects. The catalogue comprises P&K designations, names, observed expansion velocity data (for all lines), references, notes, the adopted $2V_{exp}$ for [OIII], HI, and [NII], distances, linear radii, and classes (B or C).

In the following, we shall concentrate on [OIII], HI, and [NII] expansion velocities. There are:
202 PN with V_{exp}([OIII]), including 41 objects with less reliable data and limits,
101 PN with V_{exp}(HI), including 12 with smaller reliability and 77 PN with V_{exp}([NII]), including 12 with smaller reliability.

Some mean values (the less reliable ones are not taken into account):
mean V_{exp}([OIII]) = 20.0 km/sec,
mean V_{exp}(HI) = 20.0 km/sec and
mean V_{exp}([NII]) = 24.3 km/sec.

For mean velocity differences between these lines possible observational selection is reduced by only taking PN with "reliable" measurements in [OIII] AND HI (54 PN), [OIII] AND [NII] (42 PN), and HI AND [NII] (48 PN):
mean V_{exp}([OIII] − HI) = 1.0 km/sec,
mean V_{exp}([NII] − [OIII] = 4.1 km/sec and
mean V_{exp}([NII] − HI) = 4.2 km/sec.

The higher velocity of [NII] is due to the wellknown increase of V_{exp} with radial distance from the star and ionization stratification, i.e. [NII] emission predominates in the outermost ionized layers.

In retrospect, the most frequent use of V_{exp} data was in correlation with linear nebular radii (r); only [OIII] velocities were taken. It was suggested that:
a) the majority of compact nebulae show V_{exp} proportional to r and a slow decrease of r for larger radii (e.g., Sabbadin et al. 1984),
b) a high velocity sequence and a low velocity sequence

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seem to exist (Robinson, Reay and Atherton 1982), c) most nebulae conform with the relation $V_{exp} \propto r^{-0.22}$ (Phillips 1984), etc.

The observed V_{exp}([OIII]) vs. r data were frequently used to study the dynamical evolution and formation mechanisms of PN, in part also by including the evolution of central stars (Sabbadin et al. 1984; Okorokov et al. 1985; Volk and Kwok 1985; Schmidt-Voigt and Köppen 1987).

Unfortunately, the data from the new catalogue do neither support a) nor b) nor c) and will be of limited value for the just mentioned kinds of studies. In Fig. 2 we show $2V_{exp}$ vs. r relations for [OIII] (Fig. 2a), HI (2b), and [NII] (2c); the small symbols denote less reliable expansion values. In Fig. 3 the true V_{exp}([OIII]) as derived from the spatiokinematical models vs. r is presented. Both quantities refer to the minor axis in case of prolate spheroids, elliptical rings etc. by assuming a linear dependence of V_{exp} with r; the largest symbols correspond to the most reliable data.

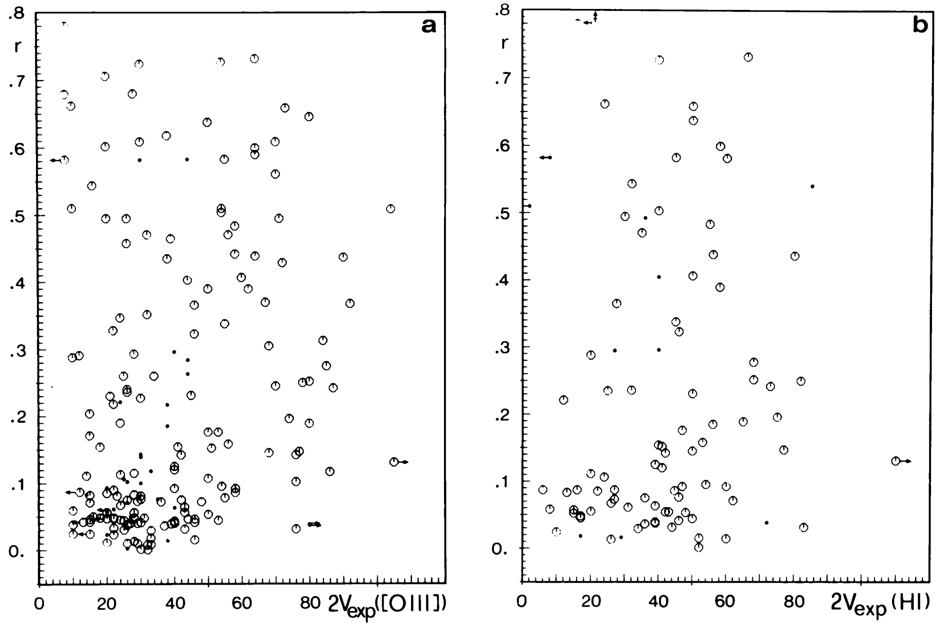

Figure 2. Observed expansion velocities vs. linear radii. 2a) [OIII] data, 2b) HI data, 2c) [NII] data. Small symbols correspond to less reliable velocities.

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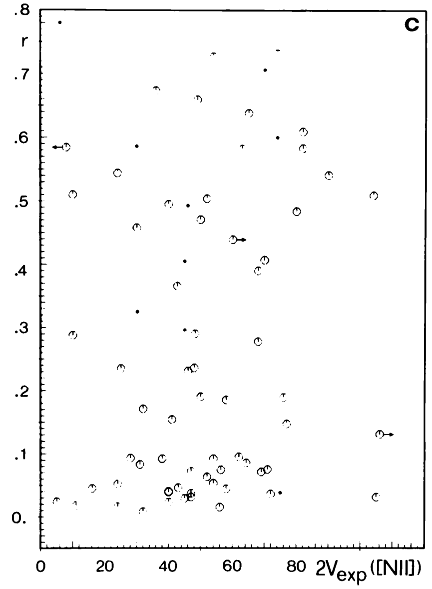

Figure 2. - Continued.

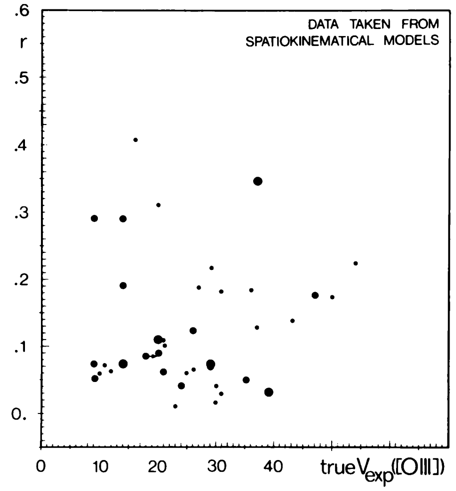

Figure 3. True (=deprojected) expansion velocities derived from spatiokinematical models versus linear radii.

Figs. 2 and 3 lead us to the following conclusions: even by considering the large effects of the various error sources, a very broad and rather homogeneous distribution (for r $\gtrsim$ 0.1 pc) is obvious that appears to reflect - at least in part - the heterogeneity in the PN population.

The scientific content of such diagrams may be better worked out by applying them to physical similar groups of PN, e.g., with respect to nebular excitation, stellar spectral types etc.; we made two such attempts in order to find out i) whether B and C nebulae can be discriminated, and ii) whether highly evolved nebulae in the galactic plane might be influenced by the interstellar medium.

The classes "B" and "C" (=non-B) were proposed by Greig (1971, 1972): B's are younger, more concentrated to the plane, have higher progenitor, central star and nebular masses, and are stronger in [NII], [OII], and [OI] emission compared to C's; these results are, in part, in connexion with the kinematically different behaviour, as Sabbadin and co-workers had suggested in many papers (e.g., Sabbadin 1984). Gieseking, Hippelein and Weinberger (1986) suggested that highly diluted, i.e., very evolved PN in the plane suffer from a deceleration of their expansion.

In Fig. 4 the $2V_{exp}$([OIII]) vs. r relation is shown for B (open symbols) and C nebulae (crosses). In Fig. 5 the $2V_{exp}$([NII]) vs. r relation for PN with $0 \leq |z| \leq 0.15$ kpc (filled symbols), $0.15 < |z| < 0.50$ kpc (open symbols), and $|z| \geq 0.50$ kpc (crosses) is shown.

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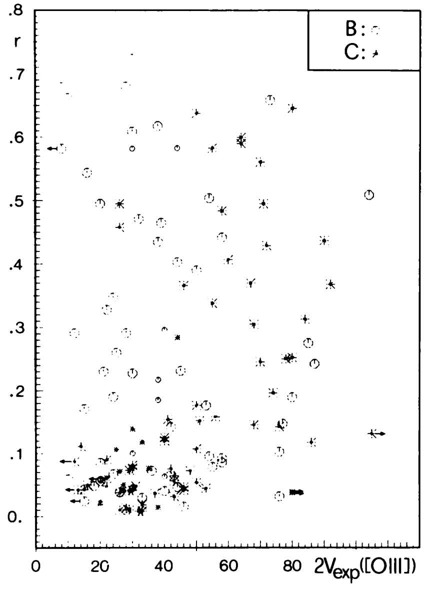

Figure 4. The $2V_{exp}$([OIII]) vs. r relation for nebulae of type B (circles) and C (crosses).

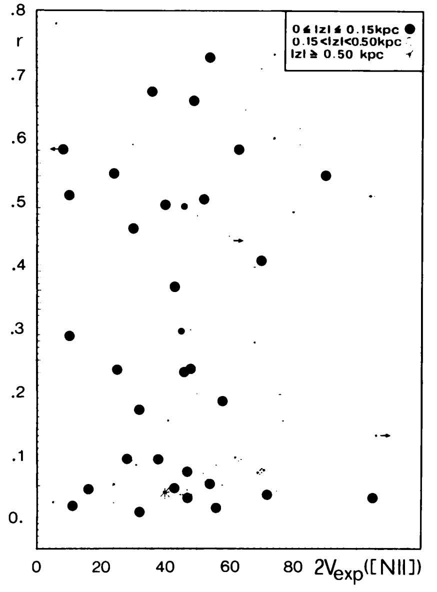

Figure 5. The $2V_{exp}$([NII]) vs. r relation for nebulae in three different $|z|$ intervals.

From both figures we conclude: it seems that both B nebulae are kinematically different (=slower) from C nebulae and that a deceleration of evolved PN in the galactic plane can occur.

5. WARNINGS AND RECOMMENDATIONS

In all above-mentioned measurements and investigations a variety of shortcomings exist - not surprising, if it is considered that this area of research is, to some extent, still in its infancy. For newcomers in this field and/or those working mainly with V_{exp} vs. r relations it is advisable to read the paper by Chu et al. (1984). Several suggestions from their article and a few own ones are presented in the following in a condensed form, as general recommendations, which may help to reduce the shortcomings in the field of expansion velocities and characteristics of planetary nebulae.

1) <u>You should try to derive detailed spatiokinematical models.</u> We need more quality instead of quantity. Concerning their importance, there are by far too few such models. Tentative models are of limited value; measure at many positions and include also the faintest possible

brightness levels.

2) Bear in mind the untrustworthiness of Vexp for kinematically unresolved PN. Usually, V_{exp} is deduced from FWHM/2 under assumption of simple expanding shells. This assumption can be quite wrong.

3) You should not measure in one line only. Remember that at least [OIII] AND [NII] (or [OII]) should be observed in order to uncover the kinematics not only in the interior but also at the surface of the nebula.

4) Relate appropriate nebular dimensions to the expansion data. In several cases it is forbidden to use, say, Hα + [NII] dimensions (from the Palomar Sky Survey, for example) and to relate them to [OIII] expansion velocities. Also, mean dimensions of a nebula should only be taken, if the V_{exp} data really refer to them.

5) When working with Fabry Perot interferometers, bear their free spectral range and the possible influence of a finite aperture in mind. These instruments usually cover a limited velocity range; high-velocity gas will escape detection. Apertures approaching the size of the nebular diameter lead to definite lower limits in V_{exp}.

6) For investigations of Vexp vs. r relations you should not treat all PN alike. Future investigations of V_{exp} vs. r relations should be pursued separately for groups of PN with similar physical properties.

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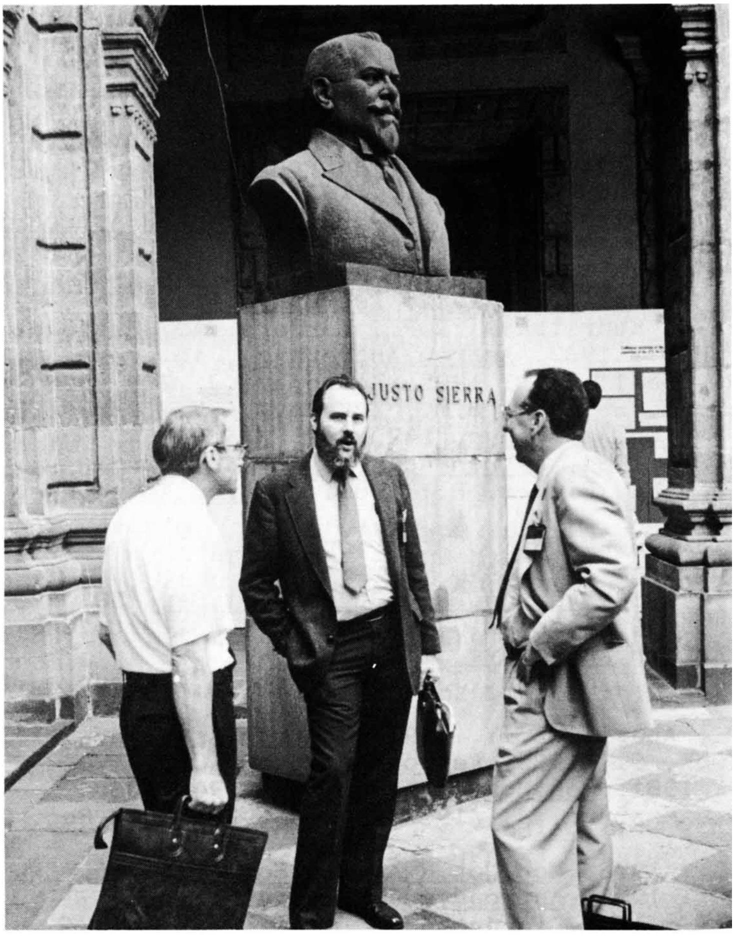

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