The kinematic evolution of the ionized shells of planetary nebulae

J A López¹, M G Richer¹, M Pereyra² and M T García-Díaz¹
¹ Instituto de Astronomía, Universidad Nacional Autónoma de México, Campus Ensenada, Ensenada, Baja California, C.P. 22860, México
² Schlumberger Foundation Fellow, School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK
E-mail: ¹ jal@astrosen.unam

Abstract. In this contribution we present the results of measuring the bulk outflow, or global expansion velocities for a large number of planetary nebulae (PNe) that span a wide range of evolutionary stages and different stellar populations. The sample comprises 133 PNe from the galactic bulge, 100 mature and highly evolved PNe from the disk, 11 PNe from the galactic halo and 15 PNe with very low central star masses and low metallicities, for a total of 259 PNe. The long-slit, echelle data are drawn from the SPM Kinematic Catalogue of Galactic Planetary Nebulae. These results reveal from a statistical perspective the kinematic evolution of the expansion velocities of PNe in relation with the changing characteristics of the central star’s wind and ionizing luminosity and as a function of the evolutionary rate determined by the central star (CS) mass. The large number of PNe utilized in this work for each group of PNe under study and the homogeneity of the data provide for the first time a solid benchmark from observations for models predictions. This project is still in progress and aims at measuring expansion velocities for about 300 more galactic PNe with the aim of providing a reliable parametric description of their expansion velocity in terms of different populations, morphologies, evolutionary stages and CS masses.

1. Introduction
Planetary Nebulae are expanding ionized shells evolving from the mass loss process in the previous AGB stage. The expanding nature of PNe was recognized nearly 70 years ago [1]. It was then inferred [2] that PNe should descend from fast-evolving, mass-losing red giant stars to eventually become white dwarfs. These ideas led to the concept of PNe originating in the ejected envelope of red giants [3] and shortly after the first basic post-AGB evolutionary model track was calculated [4] starting with an AGB star with an electron degenerate core and a H shell burning envelope. The times were ripe to realize then that the AGB envelope is the precursor of the PN [5]. However, the shells of AGB stars need additional pressure to keep an expanding motion after being ejected and various mechanisms involving ionization fronts and radiation pressure on gas and dust were explored with unsatisfactory results, until it was concluded [6] that mass loss from active stellar winds was needed to maintain the shell expansion. This problem was originally solved through the interacting stellar winds model (ISW) [7] [8] where after the initial AGB mass loss phase the exposed core of the now much smaller star becomes hotter and mass loss through radiation pressure develops a faster wind that interacts with the previous slower wind from the AGB producing a shocked interface between the two. The ISW model provides...
the mechanism to keep the ejected material expanding and the tools to understand the basic PN shapes produced by this slow wind - fast wind interaction. Once the central star evolves off the AGB stage and becomes even hotter the combined effects of the interacting winds and the ionizing luminosity over the nebula drive and dominate the shell expansion. In the energy-conserving case the ISW model predicts expansion velocities of the order of 30 km s\(^{-1}\) which agrees well with the average results of individual observations. The ISW model became the new paradigm to understand the formation and evolution of PNe, although we now know it does not explain many salient features of PNe discovered at later times with high spatial resolution (e.g. with the HST) and that clearly demand introducing additional elements to the original model. However, the ISW model remains a solid foundation of PN evolution and it is a fundamental input into all modern evolution models.

Although there are many works devoted to exploring the detailed kinematics of individual PNe, in contrast there have been few attempts to relate in a statistical way their global expansion velocities as a function of evolutionary status and compare the results with model predictions. Early attempts [9] tried to derive a relationship between the expansion velocity and the PN radius but using an heterogenous sample from different sources, obtaining a poor correlation. However, from a relatively small sample of observations with the IUE a positive correlation between the expansion velocity and the wind’s terminal velocity was found [10]. Positive correlations were also found in the Magellanic Clouds [11] [12] between the expansion velocity and the excitation class. In general terms we know from observations and models that the mean expansion velocity of PNe lies between 15 - 40 km s\(^{-1}\). We also know that the expansion velocities of PNe should evolve throughout their lifetimes as a function of the central star stellar wind, ionizing radiation and rate of CS evolution. However the available studies up to now do not provide enough information to draw a clear, parametric map of the kinematic evolution of diverse groups of planetary nebulae. This task requires measuring global expansion velocities, in a consistent way, for a large number of PNe divided by evolutionary stages, galactic populations, CS masses and metallicities. For this purpose we are using the SPM Kinematic Catalogue of Galactic PNe [13]. This catalogue contains long-slit, echelle, kinematic data for nearly 700 PNe. The spectral resolution in the data ranges from 6 km s\(^{-1}\) to 11 km s\(^{-1}\), perfectly adequate to resolve the internal kinematics of PNe.

2. Kinematics and spatial resolution

For ground based observations it is relevant to distinguish between spatially resolved and unresolved cases. In the case of resolved cases, such as large PNe from the disk, the line profiles usually present either splitting of the emission line profile or an asymmetric profile, only very few cases with very low expansion velocities present symmetric gaussian-type, single profiles. The slit in these cases intersects only a small fraction of the object. For the unresolved cases, such as PNe in the halo or some cases in the bulge, the PNe are nearly point sources and the entire object, or most of it falls into the slit. In these cases the line profiles are either a single, symmetric profile or asymmetric, barely resolved profiles. For the cases with line splitting the expansion velocity of the nebular shell is derived as half the peak to peak difference between the main receding (redshifted) and approaching (blue-shifted) components of the line profile. When the emission line is a single symmetric profile we fit a gaussian profile and assign half the resulting FWHM after correcting for instrumental, thermal Doppler and fine structure broadening, if needed. Lastly, for asymmetric and barely resolved profiles we fit red and blue gaussian components and assign the expansion velocity as half the peak to peak difference.

From the description above it is clear that the global expansion velocity is defined here as the emission weighted expansion or bulk outflow velocity for the matter projected within the spectrograph slit. As such, this \(V_{\text{exp}}\) is an adequate parameter for characterizing the kinematic evolution of the ionized component of PNe. However, it should be noted that this \(V_{\text{exp}}\) may be
unsuitable for determining kinematic ages or expansion parallax distances, for which the outer shock velocity, which cannot be measured directly, or other pattern of velocity may be a better option in some cases [14].

It should also be noted that our sample does not seem to contain PNe with a marked rim/shell structure and a hot X-ray emitting bubble, though some may be present in the bulge sample (spatially unresolved). In some models [15] the ISW mechanism causes that all PNe form and sustain throughout most of their lifetime a hot bubble produced by the fast, shocked stellar wind, contained by a rim and an outer shell. The mass loss is considered in these models always isotropic and resulting in a spherical and uniform envelope. The rim is dense and bright but moves slowly whereas the shell is fainter but expands faster. As a consequence the line profiles must contain four components, the two inner and brighter ones corresponding to the receding and approaching sections of the rim and the outer, fainter components corresponding to the shell. In this situation the global expansion velocity takes a non-ballistic structure and defining a mean, global expansion velocity requires additional assumptions. However our sample of large, evolved, spatially resolved nebulae has been chosen specifically to contain only PNe with no rims or filamentary shell structures. The sample of PNe from the halo, spatially unresolved, descend from very low mass progenitors and it is as yet unclear whether they form or preserve a hot bubble and a rim/shell structure for a long time due to their very slow evolution. As for the bulge sample, also largely composed by unresolved objects with diverse properties, there is a possibility that in this case some rim/shell type PNe may be present here but their possible inclusion in the sample may only mean that we underestimate their relative weight in the region of high $V_{\text{exp}}$, since for their characteristics, rim/shell PNe are of high excitation, but they would not alter in a significant way the general statistical conclusions of this work. Incidentally and contrary to expectations, rim/shell nebulae that host hot X-ray emitting bubbles do not seem to be pervasive. From a 1.5 kpc volume limited CHANDRA survey in the solar neighborhood it has been found [16] that only 27% of the surveyed PNe show extended X-Ray emission indicative of the presence of a hot bubble.
3. The bulge PNe sample

Here we aim at obtaining systematic observations of a single galactic population of PNe, spanning from the earliest evolutionary stages until the cessation of nuclear burning. The detailed individual results for the studies of this group have appeared in [17][18]. There are 133 PNe observed in this group. Line intensity ratios of $I(5007)/I(H_\beta)$ and $H_\beta$ luminosities ($L_{H\beta}$) have been used to discriminate (broad) evolutionary stages in the sample by adopting $I(5007)/I(H_\beta) \leq 3$ and high ($L_{H\beta}$) for (24) young PNe; $I(5007)/I(H_\beta) \geq 6$ and high ($L_{H\beta}$) for (86) mature PNe, additionally subdivided by the presence or absence of He II 6560. And finally $I(4686) \geq 0.5 I(H_\beta)$ for the (23) more evolved PNe in the bulge sample. In this way we identify 4 groups within the sample, see Figure 3, whose expansion velocities clearly increase with excitation conditions.

![Figure 3](image)

**Figure 3.** The approximate distribution of evolutionary stages of the PNe sample from the bulge as determined from excitation conditions are shown over a sketch version of the the H-R diagram [19]

For young PNe we find an average $V_{exp} = 10.7$ km s$^{-1}$, for warmer nebulae $V_{exp} = 15.7$ km s$^{-1}$, for hot nebulae $V_{exp} = 23.6$ km s$^{-1}$ and for the nebulae with the highest excitation conditions in these groups, $V_{exp} = 26.5$ km s$^{-1}$. See Figure 4. There is a very good agreement between the CS evolutionary stage and the expansion velocity with a clear trend of increasing $V_{exp}$ as the PN evolves.

4. The mature and highly evolved PNe sample

This sample aims at testing the global expansion velocity of PNe at late and very late evolutionary stages. These are relatively large, old nebulae located in the disk and composed of a single, closely spherical, smooth shell with no rims or filamentary structure. The sample is broadly divided into two groups, namely, mature PNe that still show some structure and bright outer edges but no rim and highly evolved PNe with low surface brightness and no inner structure. The detailed results of the study of these groups have appeared in [20]. There are 100 PNe in this group, 22 of them are considered mature and 78 highly evolved. The mature PNe concentrate around the "knee" in the evolutionary tracks, that is near the maximum effective
Figure 4. The expansion velocity distribution in the bulge sample is shown in colors for the different groups and in black for the mature and highly evolved sample. A continuous progression in $V_{\text{exp}}$ with excitation degree or evolutionary stage is apparent.

temperature in the evolutionary tracks, and they show the highest expansion velocities of both groups with a mean $V_{\text{exp}} = 37 \pm 4$ km s$^{-1}$. The highly evolved group are distributed mostly along the low luminosity and cooling evolutionary tracks that lead to the white dwarfs zone. This group shows a decrease in expansion velocity with respect to the mature PNe, with a mean $V_{\text{exp}} = 28 \pm 10$ km s$^{-1}$ which is in contrast with the previous trend. From the bulge sample and continuing with the group of mature PNe a clear positive correlation of increasing expansion velocity with increasing evolutionary stage, excitation conditions and central star effective temperature is apparent, see Figure 4. However, once nuclear reactions cease and the ionizing luminosity and presumably wind power decline rapidly, this trend no longer continues and the observed expansion velocity slows down. What appears as a deceleration of the expansion velocity in the highly evolved PNe near the end of their life may have additional contributions from effects such as ionization stratification, decreasing optical thickness, interaction with the surrounding medium and recombination of the outer shell regions in some cases. Overall we find that the more evolved and hotter the CS the faster the PN expansion, up to the point when the CS luminosity and stellar wind decline. At this stage this correlation breaks and $V_{\text{exp}}$ seems to start to decline.

5. The halo and low metallicity sample

With this sample we aim to characterize the expansion velocities of PNe with very low mass progenitors ($\leq 1 \, M_\odot$) and slow evolution rates. The sample contains all the PNe that have been previously classified as belonging to the galactic halo (11 objects) and PNe with log(O/H) + 12 $\leq$ 8.0 dex (15 objects) most of them located in the bulge. The selection of the second group is based on the assumption that PNe with very low metallicities also descend from very low mass progenitors. The detailed results of this work can be found in [21]. The main outcome of this study is that the expansion velocity distribution of both samples behave very similar indicating that although the groups may arise from different populations there is indeed a common link.
Figure 5. Distribution of the expansion velocities for the halo and the low metal groups. In both cases measurements obtained from each emission line are plotted. Both groups behave very similarly and regardless of the emission line considered most of the objects show low $V_{\text{exp}}$ related to the stellar parameters of this kind of PNe that drives $V_{\text{exp}}$ in these objects. In addition it is found that these groups show the slowest expansion velocities of all previous groups studied so far with mean $V_{\text{exp}} \approx 19$ km s$^{-1}$ for all the emission lines considered ($H\alpha$, $[\text{N II}]$ and $[\text{O III}]$). Our kinematic observations are in excellent agreement with [22 -25] for the 4 halo PNe that we have in common. The objects with the highest expansion rates are also those located at high effective temperature, as has been the case in the others samples. However their average $V_{\text{exp}} \approx 25$ km s$^{-1}$ is substantially lower than what is found for the mature PNe ($V_{\text{exp}} \approx 37$ km s$^{-1}$). We notice that according to some models [26] PNe with low metallicity have lower wind luminosities but also due to poor line cooling efficiency their electron temperature increases and tend to accumulate thermal pressure that drives a faster expanding shell than in PNe with normal abundances. Although the physics is sound behind this argument, this is contrary to our results for both groups in this sample where the opposite is observed, as mentioned above. Since the mass loss processes and rates of evolution from the AGB to the PN stage are poorly known for these groups further advances on theory and additional observations at higher spatial and spectral resolution are required to clarify this effect.

6. Conclusions
We have presented here the results of several works that cover a systematic and homogenous set of observations aimed at characterizing the expansion velocity of PNe as a function of evolutionary stage, considering diverse populations and CS masses. The global results from the samples considered here are shown in Figure 6. This figure shows for the first time a snapshot of the kinematic evolution of PNe as the CS evolves towards higher effective temperatures. For each group the number of members that have been measured and the average $V_{\text{exp}}$ are indicated. Notice that even for the PNe with low CS masses, the halo and low metal groups, their lowest expansion velocities appear at the low $T_{\text{eff}}$ boundary of the sample whereas the higher expansion velocities are found at higher $T_{\text{eff}}$ just as in the other samples, though at different (lower)
velocity ranges.

![Diagram](image)

**Figure 6.** The approximate distribution in the H-R diagram of the groups presented in this work are shown over evolutionary tracks [27]. For each group are indicated the number of members measured and their average $V_{\text{exp}}$. The kinematic evolution of PNe with evolutionary stage is evident in this figure. $V_{\text{exp}}$ increases with $T_{\text{eff}}$ in all cases, for the bulge and disk PNe and for the halo and low metal PNe, reaching maximum $V_{\text{exp}}$ values at the point of maximum $T_{\text{eff}}$ though within different velocity ranges that indicate a dependence on CS masses and possibly metallicity. Labels at the top of the diagram point to the groups from the bulge. Labels on the left of diagram point to the mature and highly evolved groups. Labels within the diagram point to the halo and low metal sample.

Our samples have not considered PNe that form rim/shell structures and contain a hot X-Ray emitting bubbles as a result of shocking winds predicted in the ISW theory. That type of PNe also show often fast collimated outflows known as FLIERS. In these cases the faint line components from the fast outer shell may escape detection [15] and cause to underestimate $V_{\text{exp}}$ at high $T_{\text{eff}}$ but otherwise it would not modify the trend and main conclusions of this work. In any case, the mature and highly evolved, spatially resolved PNe do not have these structures. There is the possibility that some PNe of the rim/shell class may be present in the sample of spatially unresolved objects from the bulge. We consider unlikely their presence in the halo and low metal sample due to the expected lower wind speeds and very slow evolution of these groups. From the 2 kpc volume limited CHANDRA survey of X-ray emission it is found that only 27% of the PNe in the sample show extended X-ray emission indicative of the presence of a hot bubble
Therefore it seems that these rim/shell PNe with hot bubbles are not ubiquitous. It may be that they always form, as expected from the theory, but are quickly disrupted by leakage of the post-shock, fast wind through a porous or partially open envelope, an effect that may be related with mass loss history and CS mass or pace of evolution. In addition, since the majority of cases of rim/shell + hot bubble PNe have extremely similar hydrodynamic structures and morphologies, this leads to suspect that their formation and preservation may be favored by certain conditions, possibly related to mass loss rate and a range of CS masses. This is an open subject that requires further attention. Lastly, the expansion velocities observed in the halo and low-met groups, both of low CS mass, do not agree with theoretical expectations. We find that these groups have on average lower $V_{\text{exp}}$ than their counterparts with higher CS masses and solar-type abundances. A better understanding of the mass loss processes and transitions times for these PNe is required together with additional observations with higher spatial resolution to better understand their structures. It is our aim to continue studying the kinematic evolution of PNe by incorporating in the future the missing classes in the present study.

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