

Galactic Planetary Nebulae and their central stars[★]

I. An accurate and homogeneous set of coordinates

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Abstract. We have used the 2nd generation of the Guide Star Catalogue (GSC-II) as a reference astrometric catalogue to compile the positions of 1086 Galactic Planetary Nebulae (PNe) listed in the Strasbourg ESO Catalogue (SEC), its supplement and the version 2000 of the Catalogue of Planetary Nebulae. This constitutes about 75% of all known PNe. For these PNe, the ones with a known central star (CS) or with a small diameter, we have derived coordinates with an absolute accuracy of $\approx 0''.35$ in each coordinate, which is the intrinsic astrometric precision of the GSC-II. For another 226, mostly extended, objects without a GSC-II counterpart we give coordinates based on the second epoch Digital Sky Survey (DSS-II). While these coordinates may have systematic offsets relative to the GSC-II of up to 5 arcsecs, our new coordinates usually represent a significant improvement over the previous catalogue values for these large objects. This is the first truly homogeneous compilation of PNe positions over the whole sky and the most accurate one available so far.

Key words. planetary nebulae: general – catalogs – astrometry – astronomical data bases: miscellaneous

1. Introduction

The determination of an accurate position is a very fundamental step in the study of any astronomical object. For stellar sources it is also very straightforward, once the position can reliably be measured with respect to reference stars with known coordinates. The success of the astrometric satellite observatory *Hipparcos* (Perryman et al. 1997) has led to a highly improved accuracy in the positions (and in their change over time) for more than 2.5 million stars in the Tycho 2 Catalogue (Høg et al. 2000). This in turn has led to a number of interesting developments in fields ranging from the local stellar population to the extragalactic distance scale. In the case of the Galactic Planetary Nebulae (PNe), *Hipparcos* observations yielded accurate positions only for a few of them (Acker et al. 1998). This was mainly due to the faintness of the central stars (CS) to be

used as positional reference or due to confusion with the bright nebulosity.

While the next generation of astrometric satellites like, e.g., GAIA (Lindegren & Perryman 1996; Perryman 2001) will make it possible to go to much fainter limiting magnitudes, bringing many more PNe within their reach, results will become available no sooner than a decade from now. In the meantime, modern ground- and space-based telescopes require highly accurate coordinates to exploit their full potential. For the Galactic PNe the situation is particularly unsatisfactory for a number of reasons. First, most PNe are extended objects and many of them do not have an identified CS, which would clearly determine the position of the object. Second, even when the CS is known, or the PN appears star-like, the actual coordinates are affected by uncertainties arising from the poor accuracy of the astrometry, from the coarse determination of the object position, from systematics in the observations, from the unknown proper motion of the CS, with the original positions often being copied to subsequent compilations without further revisions, etc. All these problems are also due to the fact that PNe have been discovered over many decades, in a number of wavelength domains (radio,

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[★] The complete Table 2 is only available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/408/1029>

optical, IR) and using a large variety of techniques and detectors with little attempt to unify the different measurements. Indeed, the most widely used references of coordinate information for PNe, i.e. the Strasbourg–ESO Catalogue (Acker et al. 1992) and its Supplement (Acker et al. 1996), provide a highly heterogeneous compilation of coordinates, many of which are only given to a nominal accuracy of few arcsec and a fair percentage is off by larger amounts than the given mean error would suggest. The lack of an accurate and homogeneous set of coordinates can be a frustrating complication when doing, e.g., multi-wavelength studies since simple position-wise cross-correlations can not be used to match objects across different wavelengths. Recently, Kohoutek (2000) has critically reviewed the status of Galactic PNe coordinates and identification using the Digital Sky Survey (DSS). While this is clearly a significant improvement on the existing compilations, we have to note that the DSS does not provide a homogeneous and global astrometric reference frame, which is exactly what we are aiming for.

2. The choice of the reference catalogue

A new coordinate catalogue for PNe must thus rely on a unique, homogeneous, reference dataset. In the IR, the DENIS survey (Epchtein et al. 1997) has already been used to this aim (Kimeswenger 2001), but its sky coverage is limited to the southern hemisphere, while the all-sky 2MASS survey (Skrutskie et al. 1997) has been completed only very recently. In the optical, the large photographic sky surveys performed using Schmidt plates (e.g. the Palomar Observatory Sky Survey – POSS) represent the most complete and homogeneous source of imaging available so far over the whole sky. All-sky survey plates have been digitized at the end of the 1980s to produce the original version of the Digital Sky Survey (DSS-I) and to allow for a better extraction of objects for the generation of the Guide Star Catalogue (GSC-I – Lasker et al. 1990). Originally aimed at providing guide stars for the NASA/ESA Hubble Space Telescope, hence the name, its scope was later extended to scientific applications. However, the cutoff of the GSC-I at relatively bright magnitudes ($m \leq 15$) admittedly represents a significant limit for it being used as a reference for the compilation of a new PN catalogue. Similarly, the USNO-A2.0 (Monet et al. 1998) did not provide all the information necessary for our project. We therefore took up the task of providing to the community a dedicated PN catalogue taking advantage of the recently released Guide Star Catalogue II¹ (McLean et al. 2000), making its gains in accuracy and homogeneity readily available.

The GSC-II (version 2.2.1) is an all-sky, multi-epoch and multi-colour optical catalogue based on the new digitization of ≈ 8000 Schmidt plates obtained from 13 photographic surveys carried out between 1953 and 1991. For each object, the GSC-II provides coordinates, photometry in up to four photographic passbands (J , F , N and V) and morphologic classification, together with the values of the semi-major axis, eccentricity and position angle. The astrometry of the GSC-II

is calibrated using Tycho-2 (Høg et al. 2000) stars and has an absolute, intrinsic, accuracy of $\approx 0''.35$ per coordinate axis. Coordinates are updated to the most recent epoch available. For the next release of the GSC-II, proper motion information will also be available from the comparison of coordinates derived at different epochs.

As a reference for the identification procedure, we have used the extended, yet unpublished, version of the GSC-II which extends down to fainter magnitudes ($J \sim 22.5$ – 23 , $F \sim 22$, $N \sim 19.5$, $V \sim 14$ – 19.5) than the public release. The identification procedure is described in Sect. 3, while the results and the identification statistics are discussed in Sect. 4.

3. The identification strategy

The procedure used for extracting the new catalogue of PN coordinates was very straightforward. Using the Strasbourg–ESO Catalogue (SEC) and its supplement, as available from CDS, we have performed a coordinate cross-correlation with the GSC-II to extract all the objects detected within a region of size 3×3 arcmin (5×5 arcmin for some larger objects) centered on the nominal position of the nebula. The actual object identification has then been done interactively, by comparing with the finding charts provided in the SEC and the second epoch Digital Sky Survey (DSS-II) images. This approach has been required firstly to guard against inaccurate input coordinates and to solve ambiguous object identifications due to the field crowding, e.g. in the galactic plane region.

To this aim, we have set up a semi-automatic pipeline interfaced by a PYTHON² script. Briefly, the pipeline browses the SEC, calls the SKYCAT³ display and uses as a reference the nominal coordinates of the PN to load from the DSS-II a 3×3 arcmin image of the field for object identification. Although this strategy is in principle biased by the actual appearance of the PN on the DSS-II, in practice we note that very few PNe are so faint to fall below the detection threshold of the image. After identification of the PN, the coordinates of the GSC-II objects are overlaid on the image display.

The coordinate reassessment is then driven either by the presence of a central star or by the morphology of the PN as resulting from the DSS-II image. To this aim, we have defined four main identification classes as:

- (i) *CS*: a CS is known or recognizable, clearly resolved from the nebular body
- (ii) *ST*: the nebula itself is stellar-like or unresolved
- (iii) *PHOT*: the nebula is either resolved or extended, with a well defined photometric center
- (iv) *GEO*: the nebula is extended, either ring-like or symmetric in general, or with a more complex morphology and no well defined photometric center.

Note that while the resulting coordinates are both accurate and highly objective, this classification is a qualitative one and is certainly dependent on the image data used, and their properties such as e.g. wavelength band, spatial resolution etc. We stress that such a subdivision of objects in different classes has

¹ <http://www-gsss.stsci.edu/gsc/gsc2/GSC2home.htm>

² www.python.org

³ Available from ESO at www.eso.org/skycat

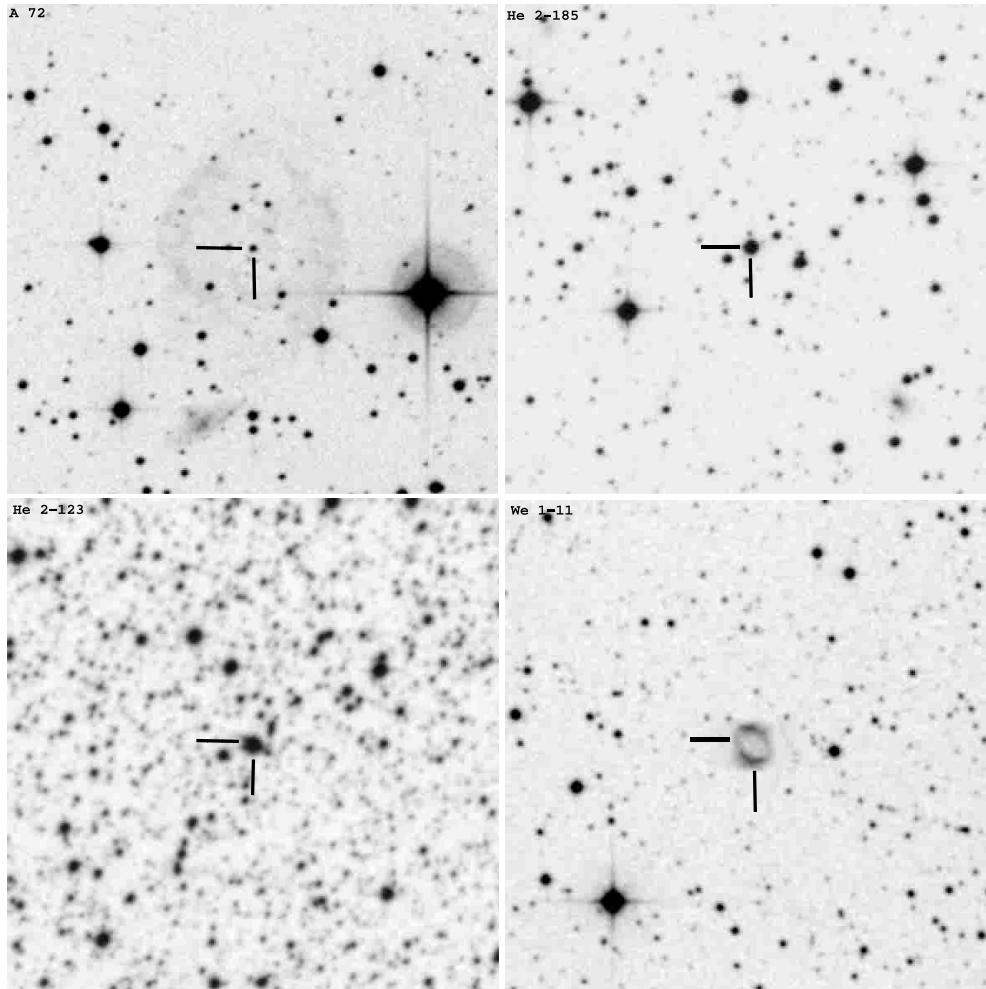


Fig. 1. Examples of the four identification classes described in Sect. 3. From top left to bottom right: *CS* (PNG059.7–18.7, A 72), *ST* (PNG321.3–16.7, He 2-185), *PHOT* (PNG323.9+02.4, He 2-123) and *GEO* (PNG091.6+01.8, We 1-11). In all cases the PN or its CS are identified by the two tick marks. The image sizes are 5×5 arcmin. North to the top, East to the left.

the only aim of serving as a guideline for our identification procedure and has no claim of providing a coherent morphological classification. Representative cases of the four identification classes are shown in the four panels of Fig. 1.

If the identification class is either *CS*, *ST* or *PHOT*, the GSC-II counterpart of the object is selected interactively with the image display cursor and its coordinates are stored in an output table together with all the relevant entries from the GSC-II. In the few cases where such an object has no counterpart in the GSC-II, which can happen when, e.g., it is detected on top of an extended emission, or in the halo of a bright star, or it is extended, its coordinates are obtained by fitting its intensity profile from the DSS-II image. Finally, if the identification class is *GEO*, the PN position is visually determined from the coordinates of its geometrical center as read from the DSS-II image. In all cases, the identification is then quality-graded depending on the confidence level of the position determination.

Although the use of DSS-II coordinates as a default solution in case of no GSC-II input certainly introduces an inhomogeneity in our catalogue, this problem will be fixed soon. Indeed, according to the plans of the GSC-II consortium (McLean 2002) the DSS-II astrometry will be entirely

recalibrated using as a reference the next version of the GSC-II. We will then use the revised DSS-II astrometry to update all the DSS-based positions obtained in the present work. Thus, all the entries in our catalogue will be finally tied to the same reference frame.

4. Results

4.1. Summary

Following the procedure described in Sect. 3, we have revised the coordinates for 1312 out of the 1528 PNe listed in the SEC plus its Supplement. The remaining ones (216) are those for which we could not rely on an identification reference, i.e., the ones which lack a finding chart in the reference catalogue, which is quite frequent for possible PNe in the Supplement, the ones for which no corresponding DSS-II image is available and the ones for which the finding chart could not be used with success. These are the cases when either the finding charts can not be directly compared with the corresponding DSS-II image (e.g. because it has been derived from narrow-band or infrared observations), or the finding chart itself provides no indication

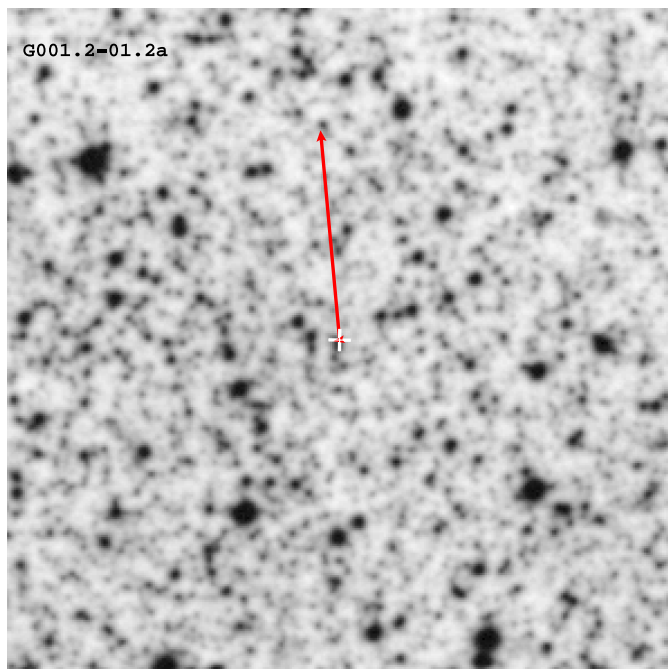


Fig. 2. The figure shows a 5×5 arcmin image of the field of the planetary nebula G001.2-01.2a obtained from the DSS-II. The cross at the center of the image corresponds to the corrected position of the PN (identification class *ST*), while the tip of the arrow points to its coordinates as listed in the SEC. The offset between the actual and catalogued positions amounts to $\sim 1'.9$.

on the object position, or it is obviously wrong. From the whole sample of 1312 identified objects we have computed their relative distribution in the different identification classes defined in Sect. 3. We found that $\sim 15\%$ are *CS*, $\sim 25\%$ *ST*, $\sim 45\%$ *PHOT* and $\sim 14\%$ are *GEO*.

Figure 2 shows an example of the measured difference between the original catalogued coordinates given in the SEC and the corrected ones in the case of the planetary nebula G001.2-01.2a. As it is seen, the actual position of the PN (marked in the figure by the cross) is offset of $\sim 1'.9$ with respect to the reference position given in the SEC (marked by the tip of the arrow). Even in less extreme cases, it is obvious that a significant error in the catalogued coordinates would yield wrong matches in any straight position-based cross-correlation. We note that using a generous search radius would just increase the number of spurious matches, thus requiring a visual validation of the results. This is especially true in very crowded regions like the one of G001.2-01.2a. Very recently, Loup et al. (2003) have given a vivid account of the problems encountered during a work similar in nature to ours but aimed at carbon stars in the LMC. They also note the inherent problems of automated cross-correlation methods and they also had to make extensive use of finding charts for proper object identification. In our case a simple cross-correlation based on position, taking the difference between the GSC coordinate and the SEC entry as the search radius would have resulted in correct GSC counterparts for $\sim 70\%$. The others have closer neighbours and therefore 30% would have been mis-identified.

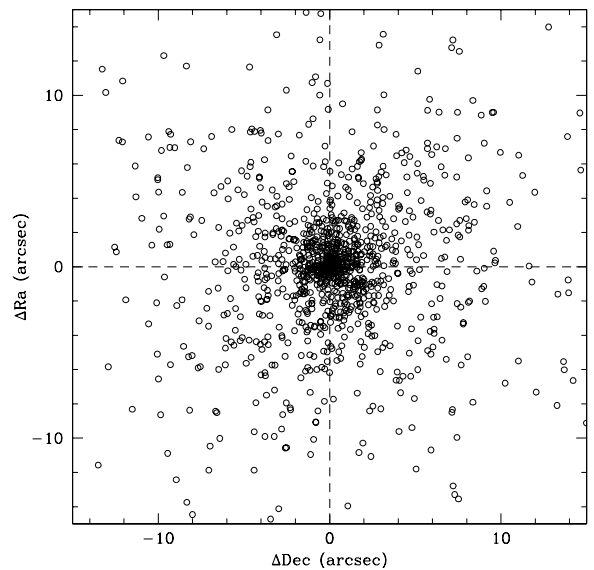


Fig. 3. Distribution of the differences in Right Ascension and Declination between the original and the corrected PNe coordinates. For clarity, only differences less than 15 arcsec have been included in the plot.

4.2. Qualitative analysis

The distribution of the coordinate differences in Right Ascension and Declination between the SEC and the revised PNe coordinates is shown in Fig. 3. No systematic effect is seen in the plotted differences, which follow a random distribution as expected from the non-homogenous compilation of the coordinates of the SEC.

From the statistics we have excluded three objects which have coordinate differences between 18 and 28 arcmin. Figure 4 shows that about 40% of the objects have Δr smaller than 3 arcsec, i.e., a value comparable with the usual tolerance on telescope pointings. However, for the majority of the objects the measured Δr are larger than 3 arcsec, which makes it either very difficult or, for non-extended objects in crowded fields, even impossible to identify them without finding-charts. In particular, we note that coordinate differences of the order of 10 arcsec or larger, as we found in $\sim 23\%$ of the cases, are sufficient to mispoint observations with narrow-field instruments like, e.g., the WFPC2/PC and the STIS on the HST. A few cases ($\sim 3\%$), with Δr larger than one arcmin, are also recognizable in the distribution. These values are beyond any reasonable error associated to the original astrometric solutions but are most likely due to a wrong or very rough compilation of the original coordinates. Some of these very large errors have been discovered and corrected over time, e.g. some improved coordinates are actually included in SIMBAD⁴. Also some errors concerning finding charts have been rectified in the literature, like the case of M 4-7, see Kohoutek (1994, 2002).

The histogram of the coordinate differences in the radial direction (Δr) for the 1312 PNe analyzed in our work is shown in the left panel of Fig. 4. The average of the distribution is 11 arcsec, with a scatter of 28. We have investigated possible

⁴ <http://simbad.u-strasbg.fr/Simbad>

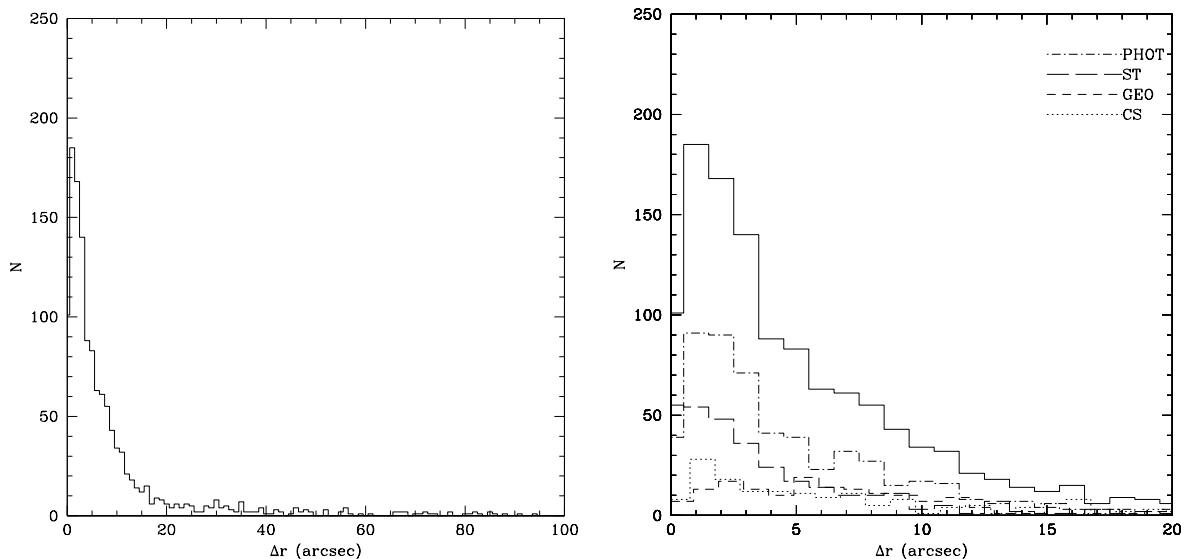


Fig. 4. (Left) Histogram of the distribution of radial offsets between the original and the GSC-II based coordinates for the sample of 1312 identified PNe. The average of the distribution is 11 arcsec with a sigma of 28 arcsec. (Right) Same, but split according to the four different identification classes defined in Sect. 3.1. For a better comparison, the histograms have been plotted on the same frame. The histograms are lines-styles coded according to the identification class.

Table 1. Distribution statistics of the coordinate residuals in the radial direction according to the different identification classes defined in Sect. 3. The first two columns give the identification class and the fraction of objects per class. The next four columns give the average of the distribution ($\langle \Delta r \rangle$), the sigma, and the minimum (Δr_{\min}) and maximum (Δr_{\max}), respectively. All the values are in arcseconds. The last row gives the global statistics.

Class	(%)	$\langle \Delta r \rangle$	$\sigma(\Delta r)$	Δr_{\min}	Δr_{\max}
CS	15	17	30	≤ 0.35	230
ST	25	8	28	≤ 0.35	479
PHOT	45	10	29	≤ 0.35	387
GEO	14	13	20	≤ 0.35	199
ALL	–	11	28	≤ 0.35	479

dependences of the measured coordinate offsets on the objects identification classes defined in Sect. 3. The histograms of the distributions of the offsets computed for the different identification classes are shown in the right panel of Fig. 4. The distribution statistics for the four classes are summarized in Table 1. Although there is no evident trend in the distribution as a function of the identification class, some differences do exist. For instance, we note that the distribution seems to be more peaked for PNe of the *ST* class than for those of the *PHOT* class. This is very likely related to the higher uncertainty in the determination of the photocenter for extended objects with respect to the star-like ones. For PNe of the *CS* class it is difficult to recognize a clear peak in the distribution which, on the contrary, is more spread in the plot. This effect could be related to possible misidentifications of the CS. These problems arise especially in the presence of bright emission knots superimposed to the nebula structure, or in case of a high back/foreground object density. The proper motion of the CS, especially when it is unknown, represents an additional source of misidentifications. Also, not all CSs are located in the geometric center of

their nebula, since interaction with the ISM can decouple their respective motion; Sh 2-174 is the most well-known example (Tweedy & Napiwotzki 1994). In these cases, strict preference is given to the position of the CS in our catalogue. PNe classified as *GEO* must be dealt with due caution, since in a large fraction of cases the definition of a geometric center is arbitrary. In particular, it depends on the nebular morphology at the observed wavelengths, on the angular scale of the observed region, which may or may not include the whole nebula, and on the symmetry of the nebula.

Although tracing back systematically the origin of the measured coordinate differences is beyond the goals of the present work, we have tried to identify and evaluate possible factors affecting the accuracy of the SEC coordinate. In particular, we have investigated possible dependences on, e.g., the galactic location of the PN and on its physical properties, like its brightness and morphology. First, we have investigated the dependence on the galactic latitude, which is obviously associated to the expected chance misidentification induced by the crowding of the field. As expected, the larger positional offsets are found close to the galactic plane, with peak values around 1'.5. For the cases where the PN has a GSC-II counterpart, e.g. for all identification classes other than *GEO*, we have also investigated a possible dependence on the object's brightness, for which we have taken its *J*-band magnitude as a reference. For the same objects, we have used the morphological information provided by the GSC-II to search for a dependence on the object's morphology. First, we selected those objects which, according to the GSC-II classification scheme, are ranked as non-stellar. Then, we have taken the object ellipticity as shape parameter. However, in both cases we could not find any evidence for a trend on a large scale. Although both the object's brightness and its non-stellar shape can influence its coordinates determination, it is clear that both play a role only if the

Table 2. Example of the format of our catalogue in its electronic version, as made available from the CDS, for the four objects shown in Fig. 1. The first column gives the PN name from the SEC or its supplement. Column 2 gives the GSC-II identifier of the object, when available. DSS-II identifications are marked otherwise. RA and Dec from the GSC-II (DSS-II) are given in Cols. 3 and 4, the galactic coordinates in Cols. 5 and 6, while Col. 7 gives the GSC-II coordinates epoch. Column 8 lists the total positional difference Δr (in arcsec) with respect to the SEC coordinates, while Col. 9 gives the corresponding position angle PA (in degrees) as measured Eastward from North. Finally, the identification class according to the definitions described in Sect. 3 is given in Col. 10.

PN ID	GSC-II ID	RA (J2000) hh : mm : ss	Dec (J2000) dd : mm : ss	l ($^{\circ}$)	b ($^{\circ}$)	Epoch	Δr ($''$)	PA ($^{\circ}$)	Class
He 2-123	S230200171244	15:22:19.360	-54:08:12.78	323.958	2.458	1992.55	4.99	145.70	PHOT
..
He 2-185	S2132023206	17:01:17.254	-70:06:03.35	321.308	-16.780	1991.65	3.17	219.42	ST
..
A 72	N031311328503	20:50:02.056	13:33:29.64	59.796	-18.729	1990.62	1.29	197.06	CS
..
We 1-11	DSS-II	21:10:52.425	50:47:14.43	91.667	1.817	1990.64	7.46	175.26	GEO

involved uncertainties are of the same order of magnitude as the precision of the original astrometric solution.

4.3. The catalogue

An example of the catalogue layout is shown in Table 2, together with a detailed description of all the provided information. The complete catalogue is made available in electronic format from the *Centre de Données astronomiques de Strasbourg* (CDS)⁵. An adapted version of the catalogue is also provided to be used directly in combination with the SKYCAT interface and to provide features like getting for each object a DSS-II preview of the field with the old and revised coordinates automatically overlaid (see, e.g., Fig. 2). It is important to caution the user that since the DSS-II astrometry is still based on the global astrometric solution provided by the GSC-I (epoch 1953.4), systematic offsets (Deutsch 1999) exist between the DSS-II and recent epochs astrometric catalogues, like the GSC-II. Thus, differences between the DSS-II and GSC-II astrometry can be substantial, ranging up to about five arcsec in some regions of the sky.

5. Conclusions

Using the GSC-II as a reference astrometric catalogue and the DSS-II as image reference, we have reassessed the coordinates of 1312 Galactic PNe, producing a highly accurate and homogeneous set of celestial positions. The identification of the objects have been individually verified on the Digital Sky Survey images. Many inaccurate coordinates have been improved and some errors found in the literature have been rectified. The derived coordinate list can serve as a reliable source of target information providing the accuracy required by modern ground- and space-based observations.

While in the vast majority of cases the measured differences can be ascribed, for whatever reason, to wrong coordinate compilations, we expect that some of those measured on the smallest angular scales are actually due to genuine proper motions of the PN and thus deserve further investigation. Using

as a reference the positional information available from the GSC-II multi-epoch plate data base we have already found the PN with the largest proper motion measured by ground-based means: Sh 2-68 (Kerber et al. 2002). Using the accurate positions presented in this paper we are expanding this to a systematic proper motion survey aimed at finding both new moving objects and at confirming the existing measurements for the known ones (Kerber et al., in preparation). An additional limiting factor in terms of accuracy is the extended nature of some of the objects and the lack of a clearly identified central star. To further improve this situation, we are conducting a dedicated study aimed at identifying some of these missing central stars using the multi-color information provided by the GSC-II in the optical and, e.g., 2MASS in the infrared. We hope that the community will find additional uses for our catalogue of PN positions.

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⁵ <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/408/1029>

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