PNe in the shopping bag of Gaia: improved statistics, distances to the microarcsec, SEDs, variability and image reconstruction

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Gaia, the next cornerstone astrometric ESA mission, has been successfully launched on November 19th 2013, just a few weeks after the conclusion of the APN6 conference. The satellite is now on the way to its final orbit located about one million and a half kilometers away from Earth. During its expected five years of lifetime Gaia will provide the first non-biased survey of the entire sky down to magnitude 20, with the primary objective of measuring parallaxes down to the micro arcsec (mas) level. Additionally, the complex instrumentation on board the satellite will provide the SED of millions of objects, mid resolution spectroscopy in the near IR, and epoch observations allowing both variability and image reconstruction studies of those sources with sizes between 180 and 700 mas. We shall review here the mission outcomes that will be relevant for the study of symmetrical and asymmetrical PNe.

1. OVERVIEW OF GAIA MISSION

Hipparcos and Gaia space missions represent the sustained effort of the European astronomical community in astrometry. The knowledge of accurate distances and movements within the Milky Way is fundamental for obtaining absolute values of the energies, dimensions and ages of the various types of stars and nebulae that populate it. Even more, it is relevant for all fields in Astrophysics, from Solar System studies to Cosmology [1].

Gaia will measure every object in the sky 80 epochs on average over its 5 years of operation, allowing both variability studies and an increase in the signal to noise ratio with time. The spacecraft instrumentation is complex and consists of two twin telescopes, each one with a rectangular 1.49×0.54 m primary mirror and a fixed wide angle between their lines of sight. The telescopes share a common focal plane, where a huge CCD (10^9 pixels) will record the light coming from three instruments. These are: the astrometric instrument, two spectrophotometers (operating in the wavelength range between 300 and 1050 nm) and a near infrared medium resolution radial velocity spectrograph [2].

It is expected that on the order of 10^{12} observations and extensive iterations be required to process the observations, with the additional challenge of a data flux of 100,000 observations per second. This is the reason why Gaia observations, together with the main properties of any observed astronomical object, will be automatically processed and derived from a software pipeline which is being produced by an international consortium, DPAC (Gaia Data processing and Analysis Consortium). This consortium arose in response to an ESA Gaia Announcement of Opportunity in March 2007, as an international collaboration with membership from all over Europe, which nowadays includes a community of more than 400 astrophysicists and data scientists [1].

1.1. Gaia: the most complete 3D survey of the Milky Way

The primary objective of Gaia is to measure positions and parallaxes of the Milky Way components with an unprecedented accuracy. It will perform a complete and non-biased survey of the entire sky for objects with visual magnitudes in the range from 6 to 20. It is expected that around 1% of the objects of the Milky Way will be observed, which corresponds to about 10^9 objects.

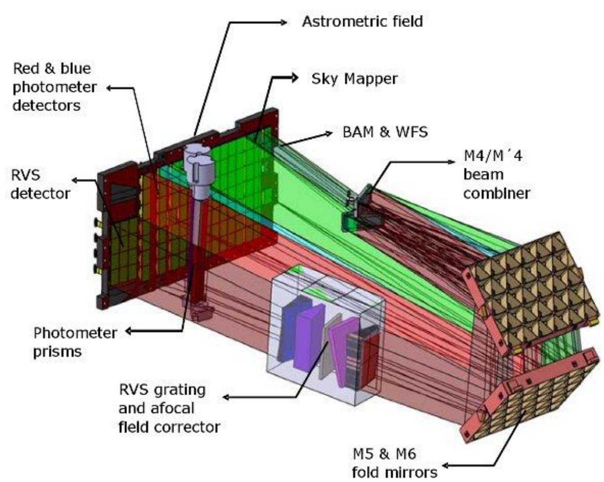

Figure 1. *Gaia instruments and the common focal plane.*

Each object will cross one of the two instrument's fields of view some 12–25 times per year, providing a good temporal sampling of variability and orbital motion on all time scales, from a few hours to years. A very accurate, dense and faint non-rotating optical reference frame will be established through the observation of quasars. This will allow high precision proper motion determinations on the sky plane. The survey will be completed by the derivation of physical, chemical and other model-based properties, mainly from the spectrophotometric observations. This adds extra- dimensions and broader scientific objectives to Gaia mission.

Gaia objectives include 26 million stars to V=15 mag that will be measured with parallax accuracies on the order of 10-25 μarcsec, and about 250 million objects to V=18 mag and parallax accuracies of 90 μarcsec. Proper motions on the order of 50 μarcsec year^{-1} for V=18 mag. are expected. Additionally, the radial velocity spectrograph will determine the third velocity component of objects down to 17 mag [3].

2. GAIA AUTOMATED REDUCTION PIPELINE: DPAC AND THE FINAL ARCHIVE PREPARATION

Since B2 phase implementation started in 2005, the development of the software system for the automated processing of the satellite data has been progressing in parallel with the hardware activities. The objective was to have a complete processing chain in place at the end of 2013. Such developments are based on simulations of Gaia observations. However, considerable further development and a fine tuning of the software is expected to happen after the launch, especially based on the experience to be provided by real data. The final catalogue should be ready three years after the end of the observations phase (2022) and it will be immediately made public to the scientific community and to the general public [2]. That will be the result of CU9 work, the Coordination Unit responsible for Gaia Data Archive preparation. Intermediate releases of some provisional results are planned after a few years of observations. Science alerts triggered by the Gaia observations (e.g., detection of extragalactic supernovae and near-Earth objects) has required the organization of a follow-up program of ground-based observations too.

3. GAIA OBSERVATIONS OF PNE

3.1. Observation principle

The satellite is continuously rotating according to a pre-defined scanning law at a nominal rate of 1 arcmin s^{-1} ; thus, the images of the stars in either field of view cross the astrometric CCDs in about 40 s.

During the entire mission, the CCD charges in the focal plane are synchronously transferred to compensate the apparent sky motion and to allow integrating the observed objects. This requires a simultaneous reading of the CCDs. However, because Gaia's focal plane is very large, comprising 106 individual detectors and almost one gigapixel, it would not be practicable to transfer its entire content to the Earth after each reading. So, the signal from the focal plane is analyzed in real-time on-board in order to detect astronomical sources. The autonomous on-board processing system detects any object brighter than 20 mag as it enters the special skymapper CCDs next to the astrometric field, and then tracks the object across the various CCDs dedicated to the astrometric, photometric and radial-velocity measurements. When sources are detected, rectangular "windows" comprising only a few arcsec around each source are created and transferred to Earth (see figure 3) [3].

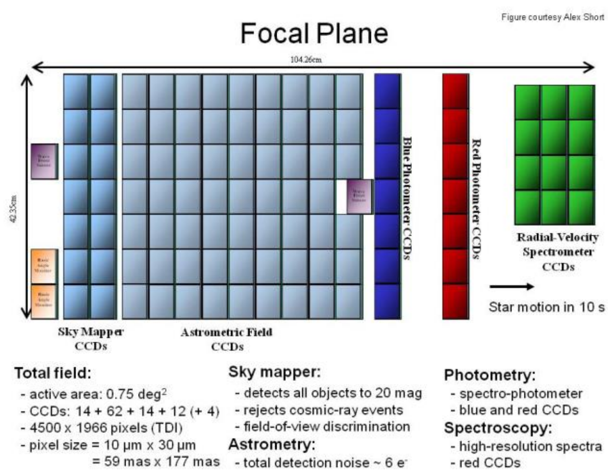

Figure 2. *Gaia focal plane showing CCD properties and several fieds corresponding to each of the instruments.*

3.2. Gaia astrometry of PNe

At the time of the Gaia Mission Critical Design Review (April 2011), the predicted end-of-mission parallax standard errors σ_π, averaged over the sky for a uniform distribution, for unreddened B1V, G2V, and M6V stars are:

	B1V	**G2V**	**M6V**
V-I_C [mag]	-0.22	0.75	3.85
Bright stars	5-14 μas (6 mag < V < 12 mag)	5-14 μas (6 mag < V < 12 mag)	5-14 μas (8 mag < V < 14 mag)
V = 15 mag	26 μas	24 μas	9 μas
V = 20 mag	330 μas	290 μas	100 μas

These numbers imply that, indeed, many Planetary Nebulae will have accurate distances at the end of Gaia mission. We expect final position accuracies of 7, 20 and 300 μarcsec at V=10, 15 and 20 mag., which turn into distances accurate to 1% out to 2.5 kpc and to 10% out to 25 kpc. The most favorable cases for astrometric measurements will be for stars in low surface nebulae, i.e. "old" PNe.

3.3. RVS spectra at 847-874 nm

RVS spectrometer covers the 8470-8740A region at R=11,500. It has been designed to use the Ca II infrared triplet lines and the H I Paschen-14 line to measure stellar radial velocities to an accuracy of better than 15 km s^{-1} down to V=17, the limiting magnitude of this instrument.

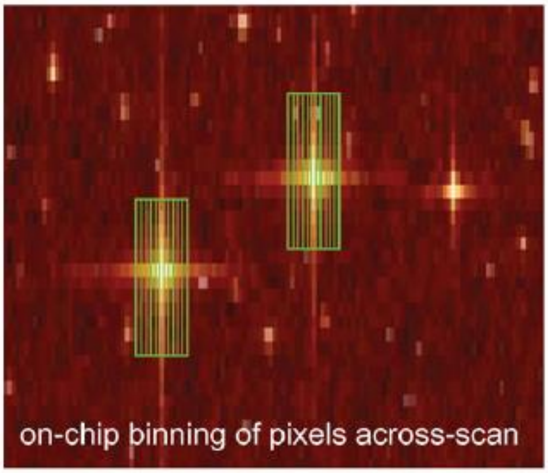

Figure 3. *Simulated CCD image of a stellar field as observed by Gaia astrometric instrument. Credits: Gaia DPAC-CU2.*

PNe, Be, WR and pre-ZAMs objects are among the most numerous point sources whose spectra are dominated by emission lines in the RVS domain. In the case of PNe, it is expected that effective temperatures for the central stars and electron densities could be derived in the RVS range by the use of models and measured line ratios. Accurate radial velocities and radial velocity variations will allow to detect new binary stars among PNe galactic populations.

3.4. BP/RP spectrophotometry at 300-1050 nm, Δλ~3-27 nm/pix

Observations from the photometric instrument would be of particular interest to planetary nebula research. Gaia blue and red spectrophotometers cover, respectively, the 3300-6600 A and 6500-10500 A wavelength ranges.

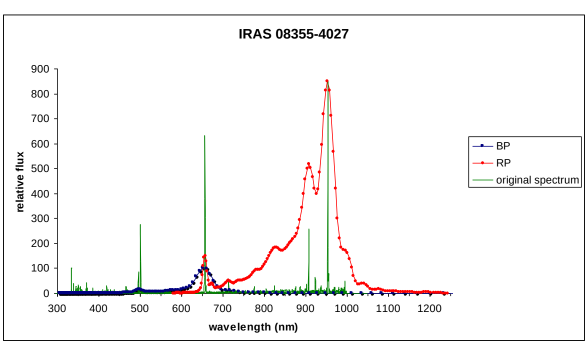

Figure 4. *Example of a BP/RP SED simulation from an observed PNe spectrum.*

The resulting spectra will have a dispersion, as a function of wavelength, ranging from 40-320 A $pixel^{-1}$ in the blue and 70-150 A $pixel^{-1}$ in the red [4]. These spectra have the potential to discover a significant number of young compact PNe and post-AGB objects with emission lines.

Most intense emission lines are visible in BP/RP simulated spectrophotometry (see figure 4). This enables to define spectral indices to diagnose the physical nature of the sources. Depending on the excitation class of the nebulae, BP/RP spectra allow to identify emission from Hβ, [OIII], Hα + [NII], [ArIII], [SII], [OII], [SIII] and Pa lines. BP/RP SEDs present a variety of morphologies that could be used to identify and classify these objects.
Gaia simulations has provided DPAC data to prepare algorithms for the segmentation of astronomical object types, and to sort the enormous quantity of data in clusters of objects with similar properties [5].
CU8 has developed an algorithm for unsupervised classification of Gaia spectrophotometric observations based on Self Organized Maps (SOM, of Kohonen neural networks). As an example, in Figure 5 we show the result of the SOM clustering of 150.000 objects belonging to CU8 BP/RP libraries, including Planetary Nebulae (PN). Purity of PNe clusters is around 97% in the confusion matrix [6]. It probes that this technique will enable to separate PNe BP/RP observations from those of other emission line objects like Be or WR.

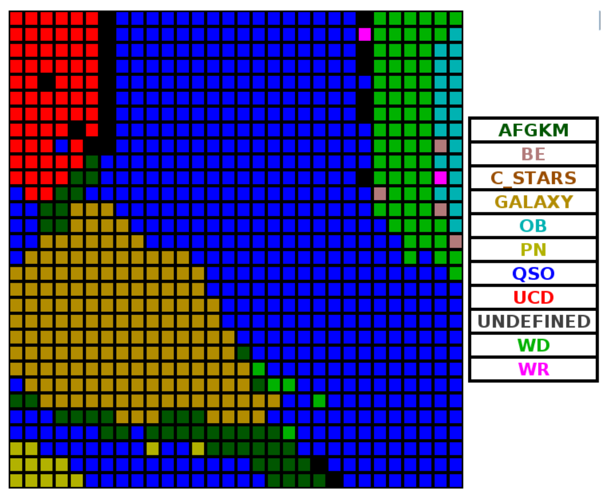

Figure 5. *SOM clustering of different astronomical objects. Every SOM unit contains a set of objects with similar SED, and neighbouring units corresponds to objects with the same physical nature.*

3.5. Gaia expected observations of extended sources

Gaia will observe many objects with a structure (extended objects) which are expected to be essentially galaxies but may also be stars embedded in star forming regions or planetary nebulae. The spectrophotometry and astrometric solution derived for these objects will allow CU8 to classify a vast fraction of them. The morphological information of the structure of these objects is present in Gaia's observations and can be retrieved. This is the objective of CU4 DU 470 (Extended Objects) which has dedicated efforts to recover and analyse the spatial structure of galaxies and planetary nebulae [7]. However, current plans are as follows: Gaia data on objects found to have angular diameters lager than 0.7 arcsec will be thrown away, i.e. not transmitted to the ground, which will clearly impact on prospects for measurements of PNe. The criteria for image profile storage and reconstruction depend on the nebula size and flux gradient. Compact "young" PNe with stepper flux gradients will be retrieved as extended sources and their morphology studied. Gaia will observe the 0.7 arcsec central region of angularly small objects with a pixel scale of 59 mas/pixel and a point spread function of 180 mas, up to magnitude 20.

4. FINAL REMARKS

At the date of writing this article (January 2014), Gaia has just arrived to its final orbit around the Earth, at L2 point. Some preliminary tests have shown that the instruments are functioning normally, and the first images of stellar fields have been retrieved. In a few years, we can expect to have an enormous supermarket where filling our shopping bag with our favorite objects. We can also expect that present statistics on central stars of PNe will substantially be improved. If we admit that central stars are being detected in 15% of known PNe [8] and if it can be expected a galactic population of about 30,000 PNe, it will imply that several hundreds of Central Stars (CS) will be discovered by Gaia.

Outstandingly, Gaia will mean a giant step with towards the determination of distances to PNe. Parallaxes of 20 μarcsec (V=15 mag) imply errors of 1% in distances to nebulae located at up to 0.5 kpc, 10% to 5 kpc and 100% to 50 kpc.

Morphological studies of compact PNe will possibly be of help in the problem of clarifying the onset of morphological PNe asymmetries. Finally, radial velocity variations will allow the discovery a meaningful number of new binary central stars.

Acknowledgments

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