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The path to life: complexity in Planetary Nebulae

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Abstract. At the age of 10^{10} yr, or earlier, the universe built living beings. Much earlier it built, and still does, other complex systems. Understanding these systems will come through physics: living complexity and inanimate complexity should share the same fundamental laws. Planetary Nebulae are complex, organized objects, and their origin, evolution and physico-chemical characteristics are relatively well understood. We attempt to quantify complexity in a sample of eleven prototypical PNe. The extraordinary bipolar PNe Abell 14 is presented and the need for new complexity metrics is emphasized.

Key words. Stars: evolution – Nebulae: Planetary Nebulae– Complexity

1. Introduction

Planetary nebulae (PNe) show a wealth of morphological structures (Corradi & Schwarz 1995) from simple round objects like A39 (Napiwotzki 1999) to extremely elaborate nebulae with many sub-structures and components (e.g. the Necklace, Corradi et al. 2011, see Figure 1). Most PNe are exquisitely ordered, armonic structures showing different types of symmetry, often including reflection symmetry (called bi-lateral by biologists). We see them, intuitively, as "complex" objects, more so indeed than "simple" spherical stars, and wonder how their complexity compares with familiar objects surrounding us, e.g. the simplest bacterium. With a broader perspective, we may ask ourselves why the universe "bothers" to build complex things.

2. Complexity in Planetary Nebulae

Identifying and measuring complexity are by no means stablished matters, and we have chosen two different approaches: 1) the *effective complexity*, basically, "the length of a concise description of a set of the entity's regularities" (Gell-Mann 1995), and 2) the *complexity index* or energy density rate, i.e. "the amount of (free) energy passing through a system per unit time and per unit mass" (Chaisson 2010).

2.1. Effective complexity

Complexity is a concept with many facets. Dodder & Dare (2000) distinguish among *static*, *informational*, and *dynamical* complexity. Static complexity would be the "structural

Fig. 1. Images of representative Planetary Nebulae. From left to right, first row: Abell 39, NGC6720, Shapley 1, Hubble 12, and Abell 14. Second row: M1-92 and Fleming 1. Third row: NGC6543, IPHASX J194359.5+170901 ("The Necklace"), NGC6302, and IPHASX J205013.7+465518 ("The Ear").

Table 1. Morphological properties of Planetary Nebulae

Object	Type	Symmetry[⋆]	N[*]	Components	Parameters
Abell 39	round	rot+ps+refl	1	1 (shell)	1
NGC6720	elliptical	ps+refl	1	1 (shell)	2
Shapley 1	round (ring)	rot+ps+refl	1	1 (ring)	2
Hubble 12	bipolar	ps+refl	1	2 (pair of lobes)	2
M1-92	bipolar	refl	2	4 (2 pair of nested lobes)	4
Fleming 1	point-symmetric	ps	3	4 (2 shells+ system of 2 jets)	>6
Abell 14	bipolar	ps+refl	3	5 (2 polar caps, central shell, 2 rings)	6
NGC6543	point-symmetric	ps	3	13 (9 rings+ 2 jets+2 shells)	≫6
The Necklace[a]	point-symmetric	ps	5	18 (shell, ring, 12 knots, 2 lobes, 2 caps)	≫20
NGC6302	(irregular bipolar)	(refl)	1	2 (pair of irregular lobes)	(2 to ∞)
The Ear[b]	(irregular)	(none)	(–)	(–)	(∞)

[⋆] Symmetry: rot=rotational; ps=point-symmetric; refl=reflection

[*] Number of sub-structures

[a] IPHASX J194359.5+170901

[b] IPHASX J205013.7+465518

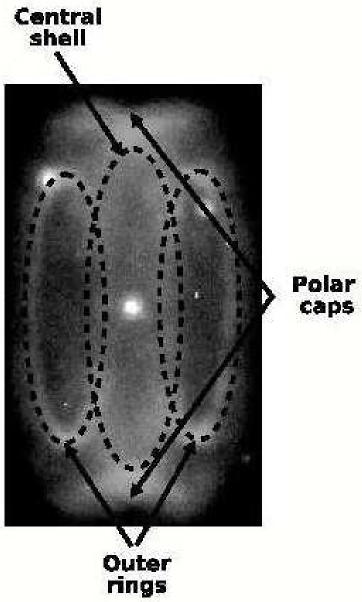

Fig. 2. Main structural components in Abell 14, superimposed on a [NII] 6583Å image from the Nordic Optical Telescope (Observatorio del Roque de los Muchachos, La Palma, Spain).

aspects of a system's complexity. Hierarchy, connectivity, detail, intricacy, variety, and levels/strength of interactions". We have analized the 2-D morphological (static) complexity in a sample of PNe (Figure 1 and Table 1). We follow Gell-Mann (1995) and identify the main 2-D morphological regularities in the PNe images (Figure 1). Table 1 shows the type of symmetry characterising each object, together with estimations of the number of sub-structures, individual components, and parameters needed to schematically describe them. While round nebulae require only one parameter (the radius), and simple bipolars like Hubble 12 require two (a parabola fits well the lobe's shape), bipolars like M1-92 ("The Footprint") require four: a cubic fit (three parameters) are needed for the lobes, plus an additional one for the separation between them.

The PN Abell 14 is probably the most appealing, although not the most complex, in the sample. It consists (Figure 2) of three main sub-structures, shell, rings, and caps, with five components: the pair of symmetric polar caps (two arcs with a central knot each) plus three elliptical rings (two brighter outer ones plus one fainter central shell). To describe the regularities of its 2-D structure requires at least six parameters: 2 semi-axis per ellipse fitted to the (assumed identical) external rings, 2 semi-axis for the central ellipse, and 2 parameters per arc (radius and angle) fitted to the four arcs of the polar caps. Other PNe like NGC 6543 or the Necklace exhibit even more sub-structures, components and regularities, and therefore require more parameters and longer descriptions, i.e. they have larger effective complexity. Note that the effective complexity of fully irregular PNe would be, by definition, zero, since they would show no regularities at all. NGC 6302 and, specially, IPHASX J205013.7+465518 (last two rows in

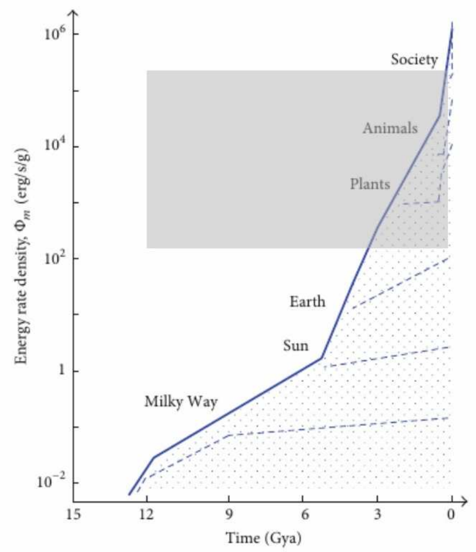

Fig. 3. The gray rectangle marks the "PNe Big History" area. Light shaded area indicates the loci of different individual types of complex systems (galaxies, stars, planets, etc.), whereas dashed lines delineate some major events during the evolution of the Galaxy, the Sun, the Earth, etc. Adapted from Chaisson (2014).

Table 1) are in this way PNe of very low effective complexity.

2.2. Complexity index

A different approach to study complexity has been proposed by Chaisson (c.f. Chaisson 2010). Figure 3 summarizes his results for a huge variety of systems, from the Galaxy to the human society, and along the whole age of the universe. The "complexity energy index" Φ_m is the rate of energy density passing through a given system, a parameter really familiar to astrophysicists that has the clear advantage to be readily calculated. The main result in Figure 3 is that structures (both living and inanimate) with larger energy density rates appeared later in the history of the universe, and they are arguably more and more complex. To locate the PNe in this graph, we take again Abell 14 as a case example and calculate its energy density rate Φ_m. Using a nebular mass of $M = 0.19 M_\odot$ from Bohigas (2003) after scaling to the actual Gaia distance of 4.3 kpc (Bailer-Jones et al. 2018), and either *a*) the luminosity of the post-AGB star at the moment of the PN formation, $L \approx 20000 L_\odot$ (assuming a $M = 4 - 5 M_\odot$ mass for the progenitor; Akras et al. 2016), or *b*) its current luminosity of $L \approx 15 L_\odot$, (Akras et al. 2016), we find Φ_m=200000 or 150 erg/s/g, respectively. These values determine the vertical limits of the PNe area in Figure 3. The horizontal limits, the duration of the PN phenomena along the history of the universe, have been plotted to be very large, covering most of the Galaxy age. The reason is that, although we do not have direct detection of the first PNe formed in the universe, we expect they appeared early from the first generations of low to intermediate mass stars in every galaxy.

The PN is a short-lived phase of stellar evolution, lasting a few $\times 10^4$ yr . Therefore, evolving individual PNe would descend from the upper regions of the PNe area in Figure 3 following almost vertical paths, and mimicking the abrupt luminosity decrease of their post-AGB central stars in their way to become white dwarfs. But the main result from Figure 3 is that PNe are located in an interesting area between living and inanimate systems.

3. Conclusions

Systems composed by a post-AGB central star (or stars) plus a Planetary Nebula are arguably the most complex large individual structures found in the Cosmos.

An attempt is made to quantify their complexity using two approaches: information (describing morphological regularities), and complexity energy index (measuring energy density rates).

Complexity researchers should ultimately propose a common metrics to compare the effective complexity of any system, from cosmic bodies to living beings.

Astrophysicists should work hard in disentangling the origins of PNe complexity. It would help understanding *the* big question: the physical origin of life.

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