DEEP OPTICAL SPECTROSCOPY AND MODELLING OF PLANETARY NEBULAE

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Abstract.

Shall we leave this millennium with a template spectrum for PNe based on photographic plates taken nearly half a century ago? Is photoionization being demolished by shock waves in PNe? Is icf getting on well with t^2?

1. Introduction

Deep spectroscopy can be defined as the effort to pursue the detection, measurement, *and* identification of spectral features to the limit of technical feasibility. This objective, a priority of Astrophysics for two third of a century, fell into a state of lethargy during the last 30 years despite extraordinary improvements of equipment. A recent quiver gives us an opportunity to consider present-day stakes in deep optical spectroscopy and conditions to make this topic to arouse from its torpor.

Past the first successes, self-consistent photoionization models of PNe did not keep all their promises. Astrophysical facts proved to be very difficult to disentangle from atomic physics artifacts. After three decades of practice, the status of photoionization modelling is still a subject of concern, raising new interrogations about the relevance of its paradigm.

A renewal of modelling may partly go through deep optical spectroscopy.

2. Deep Optical Spectroscopy

I first present a few aspects of line identification in nebulae, using the example of the planetary nebula NGC 7027, whose importance has never been dismissed due to its high surface brightness and rich spectrum. The state of the art and some conditions for future development are delineated. Complementary information can be found in Péquignot (1996).

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2.1. HISTORICAL OVERVIEW

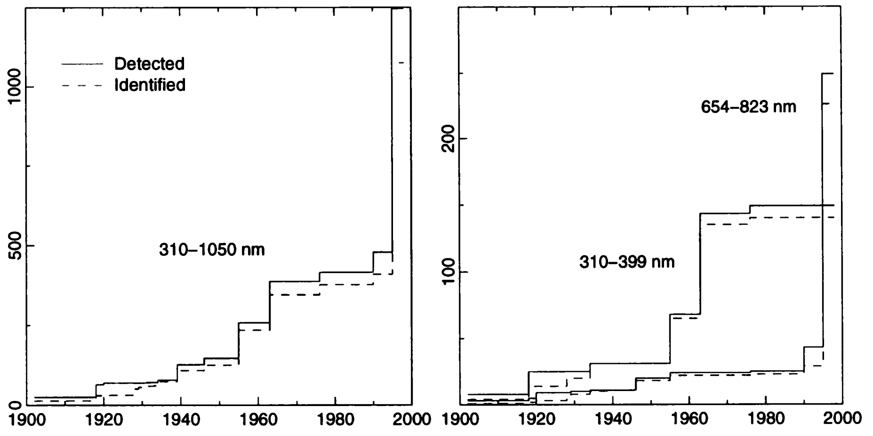

Figure 1. Number of detected (solid lines) and identified (dashed lines) emission lines in the optical spectrum of NGC 7027 from year 1902 to year 1996. Until 1938 emission lines from Orion Nebula and a few planetary nebulae are also included. (a) Left frame: wavelength range 310–1050 nm. (b) Right frame: "near ultraviolet" 310–399 nm, which most increased in 1963, and "(near-) far red" 654–823 nm, which most increased in 1995.

The solid line in Fig. 1a shows the number of emission lines detected in the 310 – 1050 nm spectrum of NGC 7027 since the beginning of our century. The dashed line corresponds to the number of identified lines.

Deep optical spectroscopy of PNe experienced two waves. A first wave (1898–1918), exploratory in nature (Wright, 1918), broke against the rocks of atomic-spectroscopy ignorance and receded for two decades. The breakthrough corresponding to the "invention" of forbidden lines (Bowen, 1928) created conditions for a second wave (1938–1963) getting its strength from a symbiosis of nebula spectroscopy with laboratory spectroscopy (Bowen & Wyse, 1939; Bowen, 1960). The resulting template spectrum for PNe (Aller et al., 1955, 1963), together with an important line-flux update partly based on photoelectric measurements (Kaler et al., 1976), has been a bible for generations of astronomers.

After the end of Bowen's scientific activity, optical spectroscopy wandered from the task of line identification, focusing on physical diagnostics and the spectroscopy of low-flux sources. Only recently was the torch passed on (Péquignot & Baluteau, 1994; Baluteau et al., 1995; the number of lines for 1996 in Fig. 1a comprises data by Péquignot et al., in preparation).

Fig. 1b compares the contrasted behaviour of the near-UV 310 – 399 nm and (near-) far red 654 – 823 nm. The line list currently in use for the near-

UV was established in 1963. The far-red exploration performed by Aller & Minkowski (1946) has not been superseded for almost half a century but the decisive progress allowed by CCD's brought this wavelength range at least to the standards of the classical optical range (Baluteau et al., 1995).

The achievement of the early 60's might have exerted a discouraging effect on the next generation, while many other attractive topics could be attacked. Nonetheless is it believable that the template spectrum for PNe be based on photographic plates taken nearly half a century ago?

2.2. TOWARDS A "THIRD WAVE"?

Why should ever deeper spectra be obtained? Recent results demonstrate that important astrophysical and spectroscopic motivations exist. Many new elements (Péquignot & Baluteau, this volume) and new mechanisms (Raman scattering: Péquignot et al., this volume; isotope-sensitive forbidden transitions: Storey, this volume) are being disclosed, opening new directions of investigation in stellar evolution, PN structure, and atomic physics (e.g., Schöning, this volume). Among other possible challenges, let us pick out the search for optical signatures of a hot gas component in PNe, the hunt for lines resisting identification, the quantitative assesement of recombination theory (Sect. 3.2), and the search for recombination lines from new elements. Without neglecting unthinkable novelties.

Recent advances in line detection (Fig. 1) were based on conventional apparatus in medium-quality astronomical conditions. Evidently we are *very far* from approaching limits of current capabilities. Technical conditions for a third wave of deep optical spectroscopy appear to be met. Will the astronomical community convince itself an effort similar to that of the 50's would be rewarding? A convergence of competences is called for.

Getting the deepest spectra is necessary but far from sufficient. Detection and identification are indissociable. Recent identifications in NGC 7027 and novae implied extrapolating known atomic levels for ions of common elements and estimating effective recombination rates by hundreds. Detailed high-quality recombination and fluorescence spectra must be computed.

The description of deep nebula spectra in terms of a list of individual lines with definite, a priori measured, intensities is reaching its own limit owing to the crowding of weak lines. Observational de-blending is partly arbitrary and generally harmful to the accuracy of component intensities. As advocated by Péquignot (1996), a new approach in terms of *spectrum synthesis* will be appropriate. The way future deep spectra of PNe will be analysed is possibly anticipated by Péquignot et al. (1993) in their study of GQ Muscae 1983, a nova in which emission lines are so broad as to make spectrum synthesis unavoidable.

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3. Photoionization Models

A model nebula is a set of (astro-) physical assumptions and a set of numerical methods solving self-consistently the equations implied by the assumptions. A set of atomic data is added to describe all known microscopic mechanisms. A specific model is defined by a set of input (astrophysical) parameters. On fitting concrete observations, *successful* inputs are effectively the *ouputs* of the model. In the important case of photoionization models, these outputs are in principle the primary-source properties, the gas- (and dust-) density distribution, and the elemental abundances.

3.1. OVERVIEW

It has perhaps not been fully realized that the fair success met by photoionization models of matter-bounded PNe three decades ago was nothing more *and nothing less* than, at last, a demonstration that photoionization by radiation from the hot central star was the main source of energy. What may well be in question here is the status of the "proof" in Astrophysics: astronomers hardly satisfy themselves with confirming a "strong suspicion". The abyss separating likelihood from proof may not make astronomers really feel dizzy, *habitués* as they are of unfathomable celestial depths!

Next steps were disappointing, mainly for not having recognized that modelling nebulae is like moving oneself through a "virtual reality", shaped by the atomic data. As noted by Péquignot (1983), the "black-box" approach, in which the atomic data set is integral part of the model assumptions, has been a passport to a realm of illusions.

Are we now in a position to consider the question of atomic data as "reasonably settled"? In all generality, the answer is certainly negative (e.g., Pradhan & Peng, 1995) but the severe problems identified by the late 70's seem to be mastered for elements $Z \leq 10$ (with some reservations at least concerning neon: e.g., Oliva et al., 1996). For example, recommending *on empirical grounds* a factor 10 reduction of the charge transfer rate for O^{2+} + H (Dopita & Meatheringham, 1991) is unrealistic (Honvault et al., 1995). Classical photoionization codes lead to quite similar results in standard conditions and these results did not much evolve during the last decade (Péquignot, 1986; Ferland et al., 1995), suggesting some kind of "convergence" (with no warranty for accuracy). Note that these codes may not yet incorporate in all details the outputs of the Opacity Project. Also the processes we may hope to disclose in PNe will often show up as small perturbations, requiring *very* reliable computations.

Last reviews on PN models (Harrington, 1989; Ferland, 1993) acknowledged the emergence of an undisputably important, fairly cumbersome ingredient in the thermal balance: the dust grains mixed with the ionized

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gas. This is provisionally a cause of concern in that an additional freedom seems to have slipped into the models. The cure – potentially a rich source of information – involves injecting ever more physical knowledge about dust and more constraints from the infrared continuum and mid-infrared solid-state spectral features (See the exemplary work by Borkowski et al. (1994) on the hydrogen-poor ejecta of Abell 30). Since neutral components may contribute to the infrared emission, PNe will have to be treated as a whole.

More scepticism is awoken by claims that the so-called "FLIERS" (e.g., Balick et al., 1994) and "BRETS" (e.g., López et al., 1995) and some high- and low-ionization lines in, e.g., the extreme PN NGC 6302 (Lame & Ferland, 1991; Rowlands et al., 1994; Bohigas, 1994) would be excited by shock waves. The analysis by Oliva et al. (1996) invites to prudence. One thing is to acknowledge that energy sources other than the primary radiation from the central star are present in PNe, another thing is to demonstrate that these sources produce direct ionization and/or line excitation to the extent they can get round supposed failures of the photoionization hypothesis. Thus FLIERS may be oddities in terms of composition or kinematics and yet be excited by photoionization (this possibility is in fact not dismissed by Balick et al., 1994). Resources of photoionization should not be underestimated. The case for extra heating will carry conviction on the condition it starts with a systematic (gas distribution, star properties, dust, etc.) and *vigilant* (atomic data, nature of the observations, extinction, etc.) exploration of all possibilities in the standard framework. The mythology of the dismaying "empirical diagnostic diagrams", that so easily flourished in weakly-constrained areas of Astrophysics, should not be encouraged: different causes can result in similar effects. Giant haloes of PNe are the seat of "extra heating": the case for mechanical heating argued by Middlemass et al. (1991) would gain in credibility after ruling out the possibility of photoelectric heating by dust grains.

Finally will the *raison d'être* of models remain the never-ending quest for the winning formula at the roulette of abundances? Considering past experience and the latent crisis of modelling (Sect. 3.2), one cannot but urge students of elemental abundances to employ empirical recipes and ready-for-use ionization-correction factors (*icf*'s) either with the most extreme weariness ... or wearing blinkers.

3.2. TOWARDS A NEW PARADIGM FOR MODEL NEBULAE?

Assuming relatively simple structures, photoionization models appear to be able to *reasonably* account for collisional line intensities in matter- *and* radiation-bounded PNe (e.g., Middlemass, 1990). Here "reasonably" signifies that the uncertainties inherent to observation and to (currently) anec-

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dotal features of PNe, notably their possibly complex geometries, cannot be *immediately* rejected as plausible causes for remaining discrepancies.

Until recently the standard way of getting a model nebula was by necessity based on a triangular reasoning in which the (strong) collisional lines were given a totalitarian power. These lines were at once (1) a major, if not unique, basis of (T_e, n_e) diagnostics, (2) the basis of ionic and elemental abundance determinations, and finally (3), as dominant coolents, the agent controlling T_e in the models. Convergence to a reasonable solution *for these lines* was then almost ensured once (1) the atomic data involved were accurate (this was the kee difference with the situation in the 70's) and (2) the basic energy requirements were fulfilled. Stated otherwise, the standard strategy was just loosely falsifiable and its success *was no indication that the nebula structure adopted was the correct one.* A (more or less) unique solution could always be exhibited, *given* (more or less) implicit secondary assumptions about, e.g., the structure. The lack of constraining redundancies effectively confined the role of models to one of "super plasma diagnostic", generally devoided (deprived?) of "creative failures".

In a seminal paper, Peimbert (1967) introduced a straightforward way to determine empirically a dimensionless "quadratic mean temperature fluctuation" t^2 from a comparison of two "mean temperatures" derived from line ratios differing markedly in their sensitivity to local temperature but sampling, as far as possible, similar volumes of gas. A comprehensive account of the method, its applications, and consequences is given by Peimbert (1995). Although mathematically clear, the t^2 concept is far from being physically simple. Along the 80's, this concept insensibly shifted to one of "local temperature fluctuations", when it was realized that existing (see above) photoionization models failed to predict sufficiently large spatial variations of temperature to account for empirical t^2's.

Péquignot (1983) could conclude that, at the end of the tortuous route followed by models during the 70's, PNe did not look more complex than what was believed before inventing models. Once bitten, twice shy? Modellers were late to consider seriously the t^2 problem, leaving too hastily a clear field to un-proved "extra-heating" alternatives. Nonetheless scepticism is now out of season (e.g., Liu et al., 1995; Barlow, this volume) and the outcome is typically within the competence of models.

A new prospect is needed since definite conclusions concerning PNe physics (gas distribution, extra heating, etc) cannot be easily reached from strategies relying essentially on collisional lines. How will the "vicious triangle" be snubbed out? A detailed photoionization model of the shell of GQ Muscae 1983 (Morisset & Péquignot, 1996) may again give us a preview of a future strategy for PNe. Thanks to overabundances, permitted recombination lines were prominent in that nova-shell spectrum and could be used to determine a priori the abundances. Collisional lines were then predicted by the model, with the shell-structure parameters left as the only freedom. Deep spectroscopy can now provide intensities for weak recombination lines in many PNe, whereas good-quality effective recombination coefficients (Storey, this volume) are being computed. After carefully checking recombination cascades by observation of reference objects in order to qualify the methods and select the most reliable emission lines, the hope that models could one day be used to check (astro-) physical assumptions and disclose structures of nebulae will perhaps turn into a reality.

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