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PEGASE: a UV to NIR spectral evolution model of galaxies

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The year 1996 saw the release by Williams et al. of the Hubble Deep Field (HDF). A whole new dimension of studying galaxies opened up to the specialist when these images became available. Galaxies of all sizes, shapes, and colors, and in great numbers, were present in this magnificent image of a minute region of the sky. As for all astronomical images, the HDF is a two-dimensional view of the sky, with no information about the distance from the observer to these many galaxies or about their age or evolutionary history. It was clear from just a quick inspection of the HDF that there were many faint blue galaxies that look irregular in shape. In principle these are the progenitors of nearby big galaxies that form by merging smaller galaxies according to the *hierarchical* models of galaxy formation. A parallel view sustains that at least big galaxies form *monolithically*; i.e., they result from the gravitational collapse of a single gas cloud in the early times of the universe and continue their evolution until the present without being substantially modified by merger events with other galaxies.

To disentangle which of these two competing views is prevalent in reality we need a three-dimensional view of the sky, in particular of the HDF. We must know which galaxies are closer to us and which are farther away. Moreover, we need information about the age of the stars in each of these galaxies. From our study of star clusters and local stellar populations, we know that stars evolve. Stellar astrophysics tells us that stars are born with physical properties such as temperature, luminosity, and size, which change in time at different rates depending on the mass of the star. The integrated colors and luminosity of a galaxy also change in time because they are the result of the combined colors and luminosity of many stars. Because it shifts the spectra of remote galaxies to the red, the expansion of the universe must also be taken into account. Galaxies that are intrinsically identical will thus look different to us when observed at different distances.

Spectral evolution models of galaxies that combine our knowledge of stellar evolution with our ideas of how galaxies form can be used to predict the colors and luminosity of a galaxy as a function of time. Cosmology provides us with extra information that relates the redshift of the light received from a galaxy to the age of the universe when the light left this galaxy. By putting it all together, we can build a true four-dimensional picture of the HDF: for each galaxy we know its two-dimensional position in the sky, its distance from us (the third dimension), and the age of the stars in the galaxy (the fourth dimension). The same procedure can be and has been applied to the many surveys of galaxies carried out from the ground and from space in the past decade.

The paper by Fioc & Rocca-Volmerange (1997) entitled *"PEGASE: a UV to NIR spectral evolution model of galaxies – Application to the calibration of bright galaxy counts"* introduced such a model to describe spectral evolution of galaxies, known by its French acronym as PEGASE. With over 500 citations in refereed papers listed in the ADS to date, the paper by Fioc & Rocca-Volmerange is without doubt an important piece of work.

The success of the paper is not related to its original intent of calibrating the bright galaxy counts. In the decade since its publication a large amount of information has been acquired about galaxy formation, evolution, and cosmology that was not known to these authors. From our present perspective, the assumptions made in the paper, and in most contemporary papers on the subject related to galaxy formation and evolution, look too simple.

Galaxies were assumed to form as single bodies in a monolithic collapse at a specific age or formation redshift that only depends on their morphological type. This means that in their model galaxies are classified in 8 morphological groups, E and S0 galaxies form at $z_{\rm for} = 20$, Sd and Im galaxies at $z_{\rm for} = 2$ and 0.5, respectively, and Sa, Sb, Sbc, and Sc galaxies at $z_{\rm for} = 5$. Assuming that each of these morphological classes evolves according to the prescriptions of the PEGASE spectral evolution model and that the universe is described by a cosmological model in which $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_0 = 0.1$, $\Lambda_0 = 0$, and $t_u = 13.5$ Gyr, they can reproduce the observed galaxy number counts quite well at the bright end in the b_J, I, and K bands.

Fitting these observations under simplified assumptions about galaxy formation and cosmology tells us that galaxy number counts are not very sensitive to the ingredients used in these models, essentially because the solution to the problem is not unique. For a set of assumptions on how galaxies form and evolve, there is always a cosmological model that produces a good fit to the counts. Once the freedom of choice of the cosmology has been banned by the WMAP results, number counts can be used to study how and when galaxies are assembled, provided we understand their spectral evolution.

The key to the success of this paper is instead the PEGASE model itself. This set of models provides a comprehensive and complete description of the spectral evolution of galaxies. All significant phases of stellar evolution are included in the tracks used to follow the evolution of stars of various metallicities in the HR diagram, including the TP-AGB and post-AGB phases. The wavelength coverage ranges from the UV (200 Å) to the NIR (5 μm). PEGASE includes a simplified nebular emission model that is linked to the number of ionizing photons in the specific galaxy model, furnishing line intensities and the nebular continuum in the same wavelength range as the stellar spectra. The models also include the effects of dust extinction using the average properties for the galaxy type and the chemical enrichment of the ISM. At the time, these two aspects were not included in similar models, e.g. Bruzual & Charlot (1993, BC hereafter).

As a result, the user of PEGASE is provided with evolving templates for galaxies of different morphologies, which include the effects of dust and nebular emission. This kind of template is useful for many applications in which the final user does not want to spend time deciding what the most appropriate model for describing the evolution of a galaxy type is or how to add the effects of dust extinction or gas emission to a purely stellar template. This apparent lack of flexibility is seen as an advantage by many users, as the high citation rate of the paper indicates.

PEGASE is not a frozen software package. The field of spectral evolution of galaxies is itself an evolving field. The main limitations of these models come from incomplete data sets of evolutionary tracks and from either empirical or theoretical stellar spectral libraries. New data sets of stellar evolutionary tracks and stellar spectral libraries are being released periodically, providing more complete coverage of the HR diagram and increasing spectral coverage and resolution. The current version of the PEGASE models, available electronically, has been upgraded by replacing the original stellar spectra by high-resolution spectra from the ELODIE data set.

Nowadays, there are many applications that benefit from PEGASE and similar codes. They range from detailed study of the spectra of distant and local galaxies to predicting the magnitudes and colors of faint galaxies in surveys to be carried out in the future, e.g. Gaia. Study of the star formation history in massive galaxy data sets, such as those produced by the Sloan Digital Sky Survey, has been possible thanks to codes like PEGASE and BC.

As often happens with this type of work, citations go to the original paper, perhaps ignoring the recent efforts of the authors and other collaborators to build a user-friendly and updated package of galaxy spectral evolution models. Knowing the authors, I am sure that they will continue their long-term project in the future.

References

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