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Review of the doctoral dissertation by Francesco Pistis, entitled
„The fundamental metallicity relation through cosmic time: from z~0 to z~1"

Metallicity in astronomy refers to the abundance of elements heavier than hydrogen and helium, primarily carbon, oxygen, nitrogen, and iron, in a galaxy's stars and gas. Shortly after the Big Bang, galaxies were primarily composed of pristine hydrogen and helium, with almost no heavy elements (very low metallicity). The first generation of stars, known as Population III stars, have formed in these conditions. They were massive and short-lived, enriching the surrounding gas with heavier elements through nucleosynthesis, stellar winds, and supernovae explosions. These enriched materials then mixed with the primordial gas, leading to the formation of subsequent generations of stars with higher metallicities. This gradual enrichment process continued as more stars formed and died, releasing heavier elements into the interstellar medium. The metallicity in galaxies is influenced by factors such as star formation rates, mergers with other galaxies, and the inflow and outflow of gas, leading to the relationship between the physical characteristics of galaxies and their metallicity. One such relationship, called the fundamental metallicity relation (FMR), is a 3D relation between metallicity (Z), stellar mass (M_*), and star formation rate (SFR) in galaxies. Understanding these relationship across different redshifts is critical for tracing the evolution of galaxies. Hence, research on this problem in the Franceso Pistis's doctoral thesis is important and timely, fitting into this rapidly developing branch of modern astrophysics, especially taking into account capabilities of the new generation of instruments like the Rubin Observatory with its LSST camera.

The candidate investigated this relationship by comparing the FMR and its 2D projections for carefully selected and analyzed samples of galaxies from the Sloan Digital Sky Survey (SDSS) at low redshifts, and the VIMOS Public Extragalactic Redshift Survey (VIPERs) at redshifts close to unity. **What is impressive is the deep understanding of the differences between the two samples of galaxies and the attempt to consistently determine the physical properties influencing the FMR in both samples.** The candidate conducted a deep analysis of various biases and methods influencing the FMR comparison. Additionally, machine learning methods were employed to investigate the FMR in the both samples, leading also to the selection of a group of interesting outlying galaxies for future more detailed analysis. The candidate’s work convincingly demonstrates that interesting and intriguing results can be obtained through such careful analysis. The PhD thesis is a compilation of three multi-author research papers, one of which has been published, one has been submitted to Astronomy & Astrophysics, and one is in preparation. **In all of them the candidate is the first author**. It is important to note that this isn’t simply a collection of three reprints or preprints, as is the usual practice in my home Institute. Instead, it takes the form of an edited book, which requires the candidate to engage in additional careful work.

I will now evaluate the dissertation chapter by chapter.

The main part of the dissertation (Chapters 4-6) is preceded by an abstract, introduction and three introductory chapters. The abstract provides a very concise overview of the work that has been done and the results obtained. In the Introduction, the candidate summarizes the context and introduce the reader to the main topics analyzed in the dissertation.

In **Chapter 1**, the candidate provides a concise yet comprehensive overview of the current knowledge related to galaxy formation, galaxy evolution, and the crucial relationships between galaxies’ physical properties explored in his dissertation. These relationships include the strong relations between the SFR and M_* - commonly referred to as the main sequence of star-forming galaxies – as well as the mass-metallicity relation and the complicated 3D fundamental metallicity relation. The chapter is very well written, demonstrating the candidate’s deep understanding of the methodologies and challenges encountered when comparing galaxy samples at different redshifts. Figure 1.10 nicely illustrates the necessity of analyzing projections of the fundamental metallicity relations, providing valuable visual insights. Additionally, Table 1.1 is an important addition, summarizing all the samples used up too now for the FMR analysis. Minor repetitions I spotted are : “dissipate energy” in Sect 2.1 on p. 6, and “considering consider” in the second para of Sec. 1.2.

Q1: *As an reviewer who is not deeply familiar with the state-of-art in extragalactic astronomy, I would appreciate clarification on the significance of the observations depicted in Figure 1.7, where all galaxies at different redshifts exhibit metallicities greater than that of the Sun (*Z_o*~8,7). I am curious to understand the implications of this finding.*

In **Chapter 2**, the latest developments in extragalactic observations are discussed. The chapter provides an overview of both photometric and spectroscopic surveys and their applications for determination of crucial galaxy properties, such as stellar mass, star formation rate, and metallicity. Notably, the discussion on metallicity includes an introduction to theory concerning line formation in galaxies’ H II regions and its application to determine the chemical composition of galaxies. I have spotted one repetition “information directly information” on p. 21, and the absence of the “=” sign in Eq. 2.4.

Q2: *Is the well-known problem in stellar astrophysics, concerning the discrepancy between chemical abundances determined from collisionally excited lines (CEL) and recombination lines (RL), also significant in the field of extragalactic astrophysics?*
Q3: *In stellar astrophysics, abundances determined from photoionization models are typically treated as the most reliable. Could the candidate comment on the remark made on p. 28 that "Photoionization models* ***overestimate*** *gas metallicity by approximately 0.2 to 0.6 dex, …"?*

Chapter 3 provides a detailed description of the large datasets used in the dissertation to explore the potential evolution of the fundamental metallicity relation. The construction of the samples at different redshift for comparison is precisely explained and analyzed in details. **Well done!**

Q4: *Unfortunately, I could not find the definitions for MAD (in the table headers) and PDF (on the figures) used in this chapter. Are they really so obvious?*

In general, the introductory sections, spanning several pages, are interesting and well organized. However, the author was unable to entirely avoid minor mistakes or a few unnecessary repetitions, which, however, do not discredit the text. In conclusion, these introductory chapters significantly enhance the reader's understanding of the depth and scope of the dissertation.

Chapter 4

In this section, various biases arising from data selection and observations are investigated to understand how they can influence the conclusions drawn from studies on the FMR and its projections. Specifically, the candidate explores the impact of factors such as the choice of the Baldwin, Phillips & Terlevich (BPT) diagram, signal-to-noise ratio (S/N) selection, criteria related to the quality of spectra, the luminosity evolution of galaxies, and the observed fraction of blue galaxies. The candidate then conducts a comparative analysis between the VIPERS and SDSS samples. The chapter concludes with a final discussion and the presentation of the research findings. This chapter, which has already been published, is highly significant for determining whether the FMR truly evolves or if biases might be distorting the conclusions, as they can mimic the evolution. An interesting conclusion from this chapter is that for a given stellar mass, galaxies with higher star formation rates tend to have lower metallicities.

Q5: *Could the candidate comment on the difference in the metallicity maximum of ~9.1 in the top right panel of Figure 4.1 and the value exceeding 9.1 in the left bottom panel of Fig 4.1. Additionally, how we can interpret the fact that for galaxies with log M_* < 9, the metallicity falls in the range of 8.7-8.9 (top left panel), yet in this same metallicity range the log SFR exceeds 1(top right panel), while for such log SFR the log M_* is around 11.5 (bottom right panel)?*

Chapter 5

In this section, the candidate attempted to understand how the applied analysis methods influence the conclusions regarding evolution of the FMR. They used several parametric methods that directly compared different projections of the FMR and carefully constructed control samples. Additionally, a non-parametric method was employed, comparing metallicity and normalized SFR in different stellar mass bins. The choice of normalization allowed for the selection of specific properties to be compare between the samples. In my view, the main outcome of this chapter is demonstration that the non-parametric methods prove to be superior tools for comparing samples at different redshifts. A noteworthy new finding is the confirmation, for the first time, of the evolution of the FMR and MZR at the redshift of the VIPERS sample. Minor repetitions I spotted are: “we report the number of galaxies in the legend” in the caption of Figure 5.1; “closer” in Sect 5.2.1 in the

Metallicity-SFR relation subsection on p. 60. In addition, the “top” in the caption of Fig. 5.8 should be replaced by the “left”.

Chapter 6

The use of VIPERS data as well as artificial intelligence (AI) for analyzing these data is undoubtedly influenced by the supervisor of the doctoral dissertation under evaluation. Nevertheless, the candidate showed ability to perform such analysis using artificial intelligence methods. This chapter is devoted to exploration of the imprints left on the FMR and MZR by underlying physical processes by means of machine learning (ML) algorithms separately on data from both the SDSS and the VIPERS survey. By applying ML techniques independently to these datasets, the candidate aimed to validate the hypothesis that the FMR remains unaffected by the galaxy's evolutionary history. He identified clusters of galaxies within the space defined by the first two principal components (PC) using the K-means clustering algorithm. Within the same space, he identified outliers. Then he investigated the cluster and outlier properties, considering various selection criteria. The performed analysis shows a power of artificial intelligence for investigating properties of the large databases. This will certainly be very important for the analysis of the future LSST data.

In conclusion, I think that Mr. Francesco Pistis’s doctoral dissertation is valuable and meets the formal requirements expected of doctoral dissertations. The candidate has demonstrated the ability to conduct scientific research effectively and possesses the necessary knowledge for the accurate interpretation of the obtained results. This leads me to recommend the admission of Francesco Pistis to the subsequent stages of the process, including the public defense of his doctoral dissertation.

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Dokument podpisany przez Ryszard Szczerba
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