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Referee's report of the PhD thesis of Mr. Unnikrishnan Potty Sureshkumar
entitled "Environmental dependence of galaxy properties using marked statistics"

The PhD thesis of Mr. Unnikrishnan Potty Sureshkumar presents the results of comprehensive researches of correlations between different astrophysical characteristics of galaxies and their spatial clustering. The samples from the galaxy surveys Galaxy and Mass Assembly (GAMA), Sloan Digital Sky Survey (SDSS) and Wide-field Infrared Survey Explorer (WISE), and mock galaxy catalogue cosmoDC2 were used as input data. The topic of the dissertation is relevant, the applied research methods are modern. The outcomes of the thesis are new and contribute to our understanding of complicated dependence of galaxy properties on their environment, in particular the clustering of galaxies.

The thesis is written in English. It consist of the abstract, list of figures (56 items), list of tables (18 items), list of acronyms, list of applicant' publication (4 items), seven chapters of the main text, extensive bibliography (275 items) and four appendices containing additional or technical material. In the first chapter the applicant give the short overview of problem and justify the actuality of thesis research. The 2nd one contains the descriptions of used observational data, galaxy surveys and catalogues. In the 3rd chapter the methods of thesis researches are described. The original results of the thesis investigations are presented in chapters 4-7. Each chapter ends by conclusions. The last eighth chapters contain the general discussion and conclusions. The main results of these chapters are published in four papers (two in A&A and two in Proceedings of the Polish Astronomical Society) in wich Mr. Unnikrishnan Sureshkumar is the first author. They was also presented in the conferences and workshop of 5th Cosmology School.

The thesis, together with the list of bibliography, appendices, figures and tables has 158 pages. It is well prepared graphically, the figures are informative, provided with comprehensive but concise captions. Wide and sincere acknowledgements expressed in the separate page of thesis indicate the sociability, sincerity and objectivity of the Author, which are the important features for a young scientist.

Description of work and main results

The first three chapters of thesis present the theoretical and practical foundations of the dissertation research. Chapter 1 gives an introduction to the current cosmology, large-scale structure formation of the Universe and its study, and introduction to the subject of Author's work. Especially, the environmental dependence of galaxy properties and its study by the methods of marked statistics are defined, and substantiated as an actual topic and advanced methods in the modern cosmology based on the galaxy surveys.

In chapter 2 Author gives the brief overview of the galaxy redshift surveys GAMA and SDSS, and mock catalogue cosmoDC2 which are used below to the study of the environmental dependence of galaxy properties. Other galaxy survey used in the work, WISE, is briefly described in subsection 5.2.1.

Chapter 3 presents the statistics methods of the large-scale structure study which are used in the work. Here Author describes how to estimate the two-point correlation function (2pCF), how to obtain the projected one, and take into account the redshift-space distortions, and estimate the uncertainties. Convenient and useful characteristics of 2pCF are the correlation radius and the degree of its approximation by the power-law function. The Author describes in section 3.7 how he compute the best-fit power-law parameters and their confidential limits. To investigate the environmental dependence of galaxy properties Author use the marked statistics, especially, the rang-ordered marked correlation functions (MCF). Their definition and method of computation, and estimation of uncertainties are given in subsection 3.9. This chapter is a kind of short tutorial on the calculation of correlation functions, with appropriate references to primary sources for a deeper understanding of the problem.

In chapter 4 the methods described above are used for study the dependence of galaxy clustering at the redshift range $0.1 < z < 0.16$ in the three separate field GAMA equatorial regions. As the galaxy properties Author use near-IR apparent magnitude limit, stellar mass limit, star formation rate (SFR) and luminosities in different pass bands (u, g, r, J, K). Here the Author presents the results of his computations of the projected 2pCF, its power-law fit and the rang-ordered MCFs. The correlation radius (5.06 ± 0.70 h-1Mpc) and degree of power ($\gamma=1.78\pm0.05$) well agree with estimations of other authors for other galaxy samples at the close range of redshifts. The rang-ordered MCFs, contrary, give the new insight on the clustering of galaxies with different their properties. Especially, Fig. 4.4 show that the stellar mass catches the galaxy over-density in small scales stronger than other properties used in this exploration. Thus, stellar mass can be considered as stronger tracer of environment than luminosity (in any passband) and SFR. Among the computed here MCFs related with luminosities in different passbands, the K-band MCF has the highest amplitude, while the u-band MCF has the lowest. It means that the K-band luminosity traces the clustering of galaxies better than any other band of those used in this work and can be a proxy for stellar mass. The SFR MCFs behave opposite to the stellar mass MCF: in all cases they are essentially lower of unity on small scales and close to unity on large scales, indicating a small number of close pairs of galaxies with strong star formation activity in the denser regions. This result support similar results obtained by other authors for other galaxy samples, which are cited. Similar, although weaker, behavior is presented by the u-band MCF. It can means that the u-band luminosity traces galaxy SFRs in the context of environment, concluded Author.

Chapter 5 contains the results of study the correlations between mid-IR properties of galaxies and environment. It was used a set of galaxy samples from the GAMA survey supplemented with mid-IR luminosities from WISE at four bands: W1 (3.4 μm), W2 (4.6 μm), W3 (12 μm), and W4 (22 μm). The two-point projected correlation functions 2pCFs in the various W1-absolute magnitude selected subsamples are computed and fitted with power-law models. The MCFs are computed using the luminosities in WISE bands, stellar masses and SFRs. All correlation functions are computed using the galaxy subsamples from four different redshift bins in the range $0.07 < z < 0.43$. The main results of this chapter show that i) the W1 and W2 band luminosities can be the better choices among all the WISE bands after stellar mass for tracing the galaxy clustering, iii) the W3 and W4 band luminosities follow SFR in general, iv) K band serves as a better proxy for stellar mass than W1 band, v) evolutionary changes of all correlation functions in the redshifts range $0.07 < z < 0.43$ are insignificant.

In the chapter 6 the Author studies how the flux limit of a survey affects the measured clustering. He computes the projected 2pCFs and MCFs on stellar-mass-selected samples in the redshift range $0.1 < z < 0.16$ using absolute magnitudes in the u, g, r, J, and K bands, stellar mass, and SFRs of galaxies as marks. He also compares the measurements in GAMA sample with those from SDSS. It is shown that MCFs are significantly affected by the flux limit, whereas the 2pCFs are weakly affected for both galaxy samples, GAMA and SDSS.

Chapter 7 is devoted to the analysis of the ability of the mock galaxy catalogue cosmoDC2 to reproduce the properties of galaxies from the sky surveys. For that the Author computes the projected 2pCFs and MCFs on stellar-mass-selected galaxies from GAMA and cosmoDC2 in the redshift range $0.1 < z < 0.16$ using absolute magnitudes in the u, g and r, and stellar mass as marks. The results show a some inconsistency between the 2pCFs and the MCFs for galaxy samples from GAMA and cosmoDC2 catalogues. The Author concluded that the cosmoDC2 mock catalogue does not perfectly reproduce the environmental dependence of the galaxy properties.

Thesis's results well agrees with the base issues of the theory of Gaussian peaks in the field of primordial perturbations (Bardeen et al. 1986) and Press and Scheckter formalism that is once more support of correctness of the inflationary paradigm and hierarchical scenario of the LSS formation. At the same time, they have scientific novelty and shed light on the complex relationship between the astrophysical properties of galaxies and their environment.

Referee's comments

The phrase in the Introduction "The dark matter interacts only via gravitational force and not via electromagnetic force. So, it is not possible to "see" the dark matter…" is correct but do not reflect the current state of dark matter problem. Now we have "zoo" assumptions about the nature of dark matter. For example, if the dark matter particles are WIMP's then they participate in the weak interaction and may be once detected in the experiments like DAMA, Xenon100, LUX etc.

Fig. 3.18 presents the main results of Chapter 3 of the statistical analysis of the correlation of astrophysical characteristics of galaxies with their clustering in the GAMA *O* galaxy sample. But these results are not discussed in any way in this or other chapters.

Fig. 5.2 illustrates that $w_p(r_p)$ of brighter galaxies is higher that means the correlation radius r_0 is larger at each z (panels). The insets in Figs. 5.2-5.4 and 7.7 illustrate the correlation between r_0 and γ for some samples: the larger is r_0 the large is γ.

This correlation is not emphasized and not explained. Would it may mean, for example, that the brighter galaxies statistically are clustered more compact?

About evolution. It seems for me that Fig. 5.2 illustrates the reverse evolution: systematic increasing of 2pCF with increasing z for sample $M_{W1}\leq$-25 (maybe in the range of 1σ uncertainties). It may hint that such galaxies which we observe at z~0.2 and at z~0.4 are formed from the initial density perturbations of different amplitudes. Galaxies at higher z are formed from the initial density perturbations of higher amplitudes which are stronger correlated (Bardeen et al. 1986). It can be third (firs two are in p. 83) explanation of the lack of redshift dependence of clustering of W1 selected galaxies.

Subsection 7.4.3 contains the results of analysis of dependence of CFs on flux limit in the *r* band (similar to the analysis in subsection 6.3.1 as it is noted in the first sentence), while in the title and in the text of subsection and section conclusions noted as “stellar mass incompleteness effect”.

The "σ differences" presented in Tab. 7.4 is not explained and not discussed.

The confidential contours in the r_0-γ planes in Figs. 3.11, 3.13-3.14, 4.5, 5.2-5.3, 5.5, 6.4-6.6, 7.3, 7.5-7.6 are not symmetrical, but the confidential ranges of best-fitting power-law parameters in the Tables 5.4, 5.5, 5.6, 6.3, 7.4 and Figs. 3.12, 4.4, 5.4, 5.9, 6.6, 7.6, 7.9 are symmetrical. In such cases the best-fitting values usually are presented in the form $y^{+\Delta 1}_{-\Delta 2}$ or y+Δ1/-Δ2.

The general remark. The two-point correlation function is not a complete description of the galaxy's environment, since it does not sense the hierarchy of the structure of the Universe and the topology of the spatial distribution of galaxies (clusters, superclusters, filaments, walls, voids). Other indicators can be used (see, for example, Hong & Dey (2015), de Regt et al. (2018), Bermejo et al. (2022) and citations therein) for nowaday and upcoming galaxies surveys. This means that direction of thesis research has perspective of extensive and intensive development.

The comments presented above do not diminish the value of the work which in my opinion provides new valuable input to the area of search for environmental dependence of galaxy properties, an important component of the study of the large-scale structure of the Universe.

In my opinion Mr. Unnikrishnan Potty Sureshkumar’s doctoral dissertation meets the formal and customary requirements for doctoral theses, and I propose that Mr. Unnikrishnan Potty Sureshkumar be admitted for father stages of his doctoral procedure.

DrSc, prof. Bohdan Novosyadlyj

Lviv, Ukraine, 5.09.2022

ЛЬВІВСЬКИЙ НАЦІОНАЛЬНИЙ УНІВЕРСИТЕТ імені ІВАНА ФРАНКА
АСТРОНОМІЧНА ОБСЕРВАТОРІЯ