The XIIIth Bulgarian-Serbian Astronomical Conference
(3rd – 7th October 2022, Velingrad, Bulgaria)

Properties of Milky way globular clusters associated with X-ray sources

Svetoslav Georgiev Botev *(PhD student at* St. Kliment Ohridski University of Sofia*)*

Assoc. Prof. Petko Nedialkov
*(*St. Kliment Ohridski University of Sofia*)*

Aim of the research

Statistical comparison (through the K-S test) of samples of GC from the MW, *located at distances between 500 pc and 120 kpc from the centre of the Galaxy and* with different integral X-ray luminosity, for which the following parameters are available:

- X-ray fluxes of individual sources in them according to Chandra, XMM-Newton and Swift missions;
- distance;
- core radius;
- extinction $E(B-V)$;
- ellipticity;
- eccentricity of the orbit;
- estimated number of black holes with intermediate mass;

Luminous X-ray sources in globular clusters are those with integral X-ray luminosity **Lx** $\gtrsim$ **10^{36} erg s^{-1}**

Why X-ray globular clusters in the Galaxy?

Di Stefano, R., Kong, A.K.H., Garcia, M.R., Barmby, P., Bright X-ray Sources in M31 Globular Clusters, 2002, ApJ, 570, 618.

For the galaxy M31 Di Stefano et al. (2002) prove statistically significant differences between 28 X-ray and ~100 non-X-ray globular clusters for the optical luminosity parameter M_V, (P=0.01) and 6 X-ray and 14 non-X-ray globular clusters (P=0.08) central surface brightness $\mu_0(V)$ by applying Kolmogorov-Smirnov test;

Kostov, A., Stanev, I., Nedialkov, P., Structural Parameters Comparison between X-Ray and Non-X-Ray Globulars in M31, 2005, Meetings in Physics at University of Sofia, 6, 86.

For the galaxy M31 Kostov et al. (2005) prove statistically significant difference (P=0.06) between 23 X-ray and 87 non-X-ray globular clusters for the ellipticity parameter $\eta=(1- b/a)$

Why X-ray globular clusters in the Galaxy?

Globular clusters are a traditional area of astronomical research in Bulgaria (Nedka Spasova, Ruscho Rusev, Yordanka Borisova, Nikola Kacharov).

• We have obtained data from current X-ray missions and also ellipticities from the catalog of Harris (2010 edition), and, in addition, other parameters from the latest researches (including number of black holes and orbital eccentricity);

•Can we prove significant statistical differences between X-ray and non-X-ray globular clusters for the parameters: ellipticity, number of black holes and eccentricity of the orbit of GCs, belonging to the Galaxy, by applying the Kolmogorov-Smirnov test?

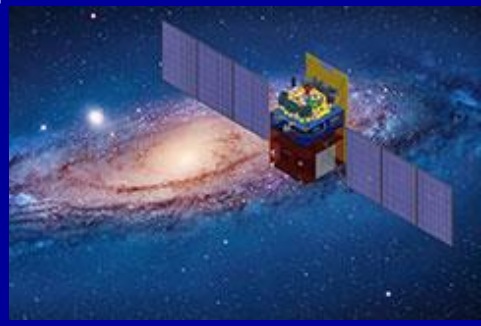
Globular clusters in the Galaxy

- $\sim$ 150 systems, containing approximately $10^5 - 10^6$ stars (mainly in the halo of the Galaxy);
- spherical symmetry -- > gravitationally connected systems (virial theorem);
- dynamical evolution: segregation by mass;
- age: >10 – 13 Gyr;
- mass: $\sim 10^4 - 10^6\, M_\odot$;
- compactness: $r_h \sim 3$ pc (set of structural parameters);
- density : $10^3 - 10^5 M_\odot / pc^3$;
- stellar density: medium 0.4 stars/pc^3 ;
  in the core 100–1000 stars/pc^3 ;
- mean M_V=–7.2 mag. ;
- low metallicity [Fe/H]< –1.2 ;
- typical separation distance between two stars $\sim$ 0.3 pc ;
- black holes at the centre of the globular cluster:
  - single BH, Maccarone et al. (2007): in a GC (globular cluster) in a galaxy of Virgo;
  - an ensemble of BH, Vitral & Mamon (2021): in the GC NGC 6397 in the Galaxy;

X-ray astronomy

- **In the beginning: the mission Uhuru in 1970;**
- **X-ray range 0.1-100 keV (10 nm – 100 pm)**
- **(0.1-1) keV „soft“, (1-20) keV „classic“, (20-100) keV „hard“ X-ray range;**
- **The most remarkable active NASA+ missions : Swift, AGILE, AstroSat, CALET, Chandra, Fermi, INTEGRAL, MAXI, NICER, NuSTAR, SRG-eROSITA/ART-XC, XMM-Newton.**

- **HXMT (2017) The Hard X-ray Modulation Telescope: (China): high (20-250 keV), medium (5-30 keV) low energy (1-15 keV) X-ray telescopes**



- **NICER (ISS) (2018): 56 bands 0.5–8keV**
- **eROSITA(2019) MPIfEP (MPE), Germany**

X-ray sources in globular clusters

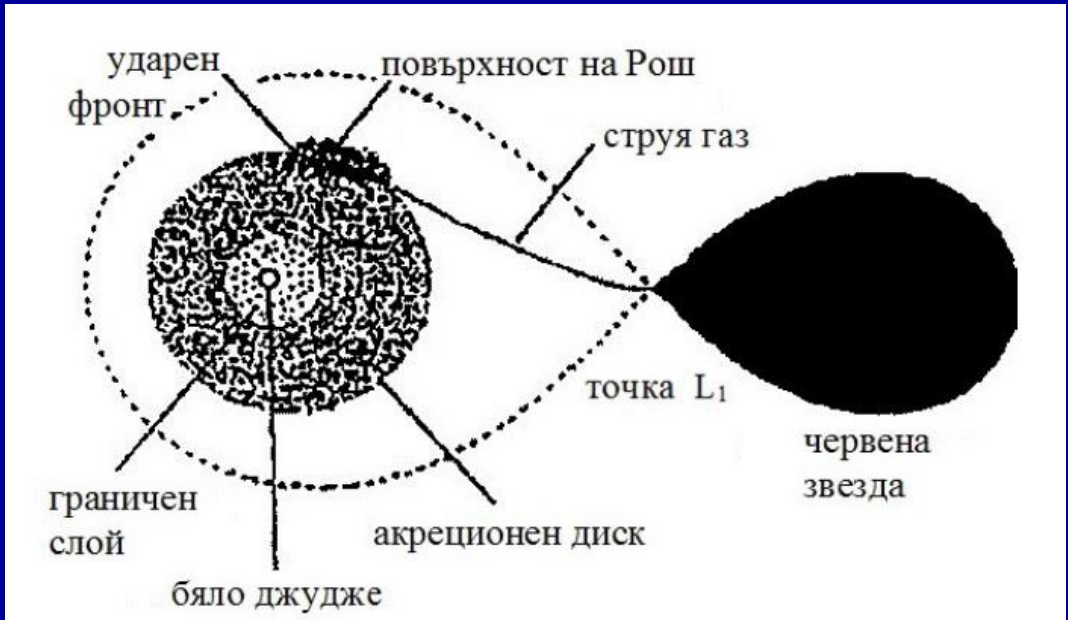
For instance, the globular cluster NGC 6397 in the Galaxy contains 15 variables of the type RS CV and 42 active sources (Cohn et al. (2010):

Variables of the type RS Canes Venatici ($Lx=10^{30}– 10^{33}$ erg/s)

X-ray pulsars ($Lx=10^{35}– 10^{39}$ erg/s)

Barsters ($Lx=10^{36}– 10^{57}$ erg/s)

Low-Mass X-ray Binaries (LMXB) ($Lx=10^{34}– 10^{38}$ erg/s)



Фигура 1.1 Акреция върху релативистка звезда в двойна система.

Input data

- According the catalog of Harris – 2010 edition, data for :
  - the nuclear radius r_c – for selection of X-ray sources;
  - the heliocentric distance R and the colour excess E(B–V) – to determine the total X-ray luminosity in the range (*0.5 – 7 keV),* with effective energy *hν=2.3 keV,* for isotropic radiation:
  - ellipticity for 95 globular clusters;

$$N_H/\mathrm{E(B–V)} = 4.8 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1} \text{ (Bohlin et al. 1978)}$$

- Lx: total luminosities Chandra, Swift, XMM-Newton for 89 globular clusters;

$$\sigma_\nu = 7.10^{-18} N_K Z^4 \left(\frac{13.56}{h\nu}\right)^3 [cm^2]$$

- estimated number of black holes: Weatherford et al. (2020) for 50 globular clusters;

$$\tau_\nu = \sigma_\nu N_H$$

$$F_\nu{}^0 = F_\nu \exp(\tau_\nu)$$

- eccentricity of the orbit: Bajkova et al. (2020) for 152 globular clusters;

$$L_{(0.5-7\,keV)} = 4\pi R^2 \sum F^0_{h\nu=2.3\,keV}$$

Data transformation of X-ray ranges of energies

The most numerous data on X-ray fluxes are included in the catalog of The Chandra Source Catalog (CSC), Release 2.0, 2010-2019, ApJS, No1 from the mission Chandra in the range of photon energies 0.5 – 7 keV, with efficient energy of the order of 2.3 keV. For this reason, data for other fluxes has been converted to this range using the following equations:

$$Chandra \rightarrow Chandra:$$

$$F_{(0.5-7keV)} = (6.5/9.9)\, F_{(0.1-10keV)}$$

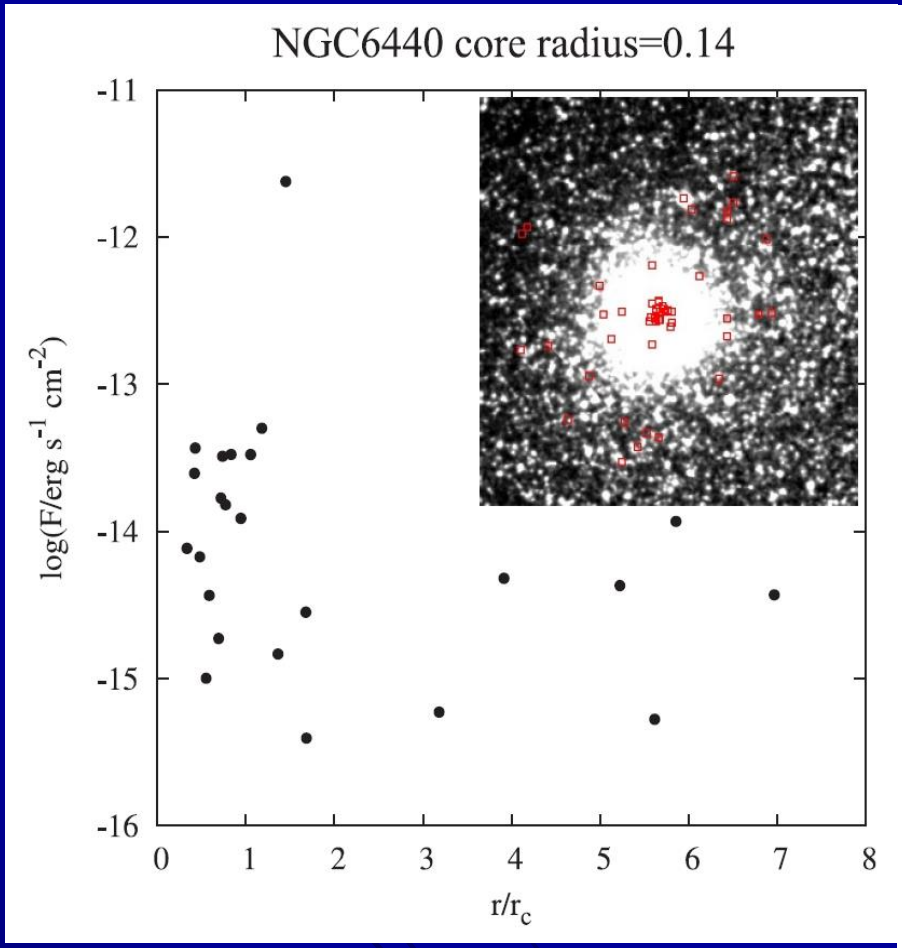
$$XMMN \rightarrow Chandra:$$

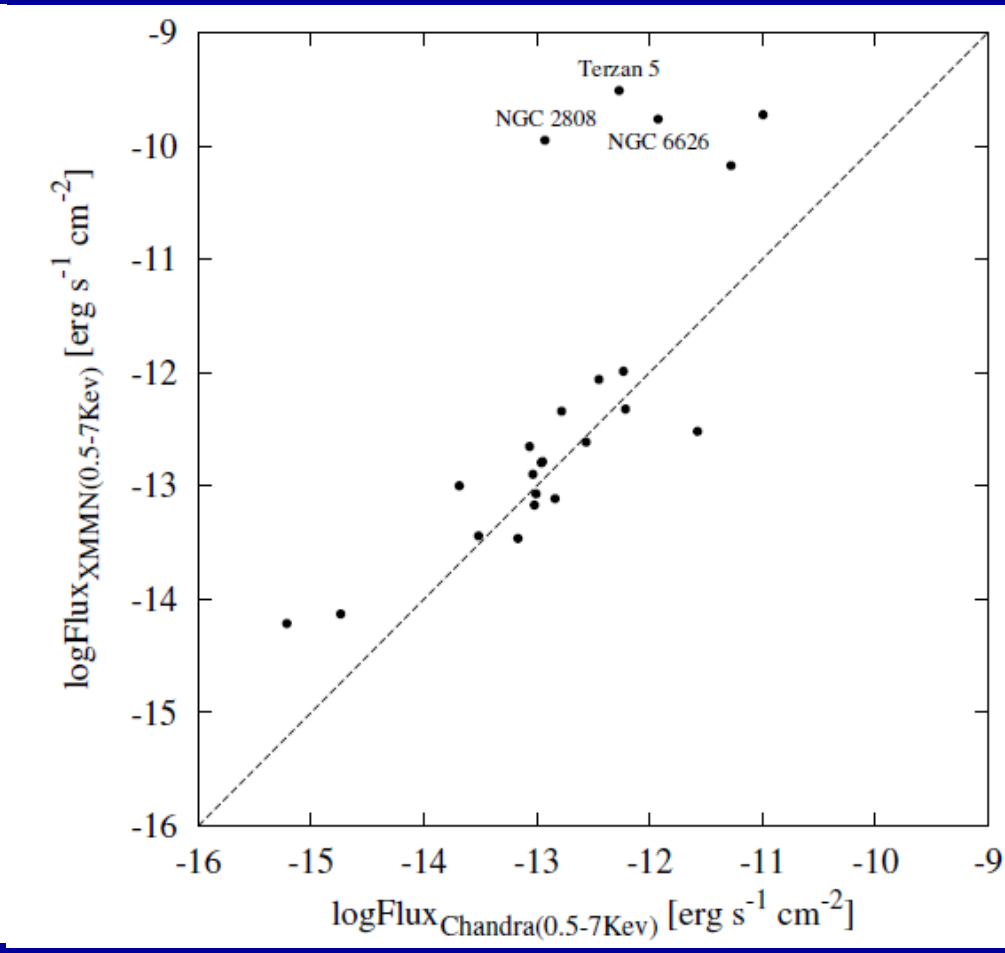
$$F_{(0.5-7keV)} = F_{(0.5-1keV)} + F_{(1-2keV)} + F_{(2-4.5keV)} + F_{(4.5-10keV)}/3$$

$$Swift \rightarrow Chandra:$$

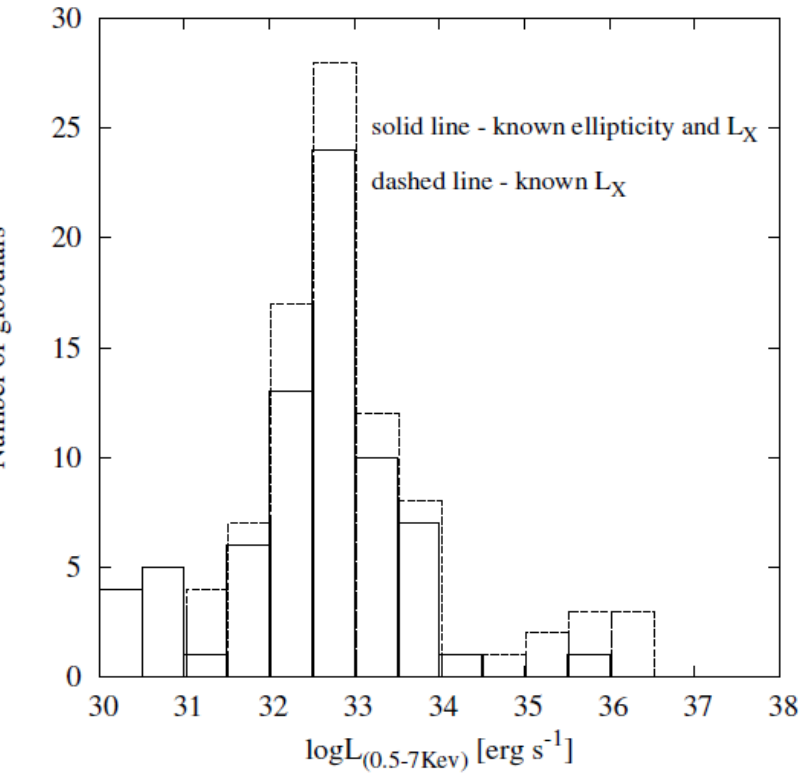
$$F_{(0.5-7keV)} = (6.5/9.7)\, F_{(0.3-10keV)}$$

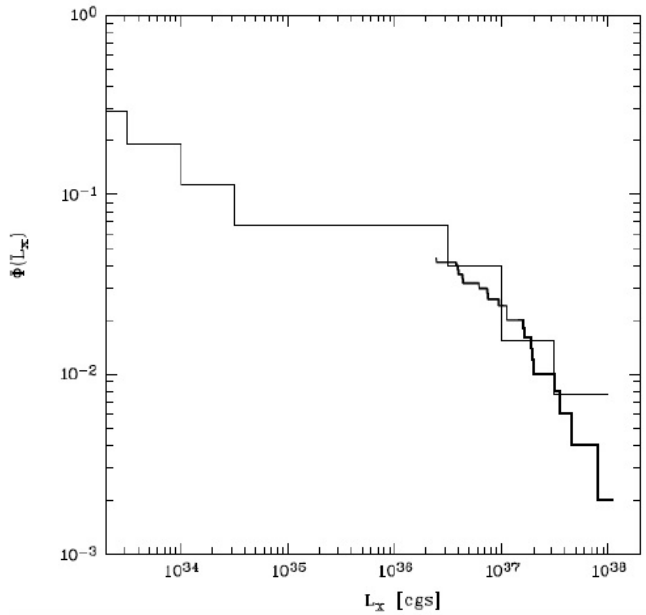
X-ray source data processing





Function of X-ray luminosity for 89 globular clusters





Фигура 2.9 Функции на нормирана рентгенова светимост за кълбовидни купове в M31 (Supper et al. 1997) и Галактиката (Hertz & Grindlay (1983).

Kolmogorov-Smirnov test

2 parameters are calculated:

D-statistician (D-stat.) – the maximum difference in the cumulative distributions of two samples

Probability P (sometimes in %) for wrong rejection of the Null hypothesis, according to which the two distributions originate from the same parent distribution, i.e. they are statistically indistinguishable.

Rejection of the Null hypothesis: small values of probability P

Results from the K-S test for ellipticity

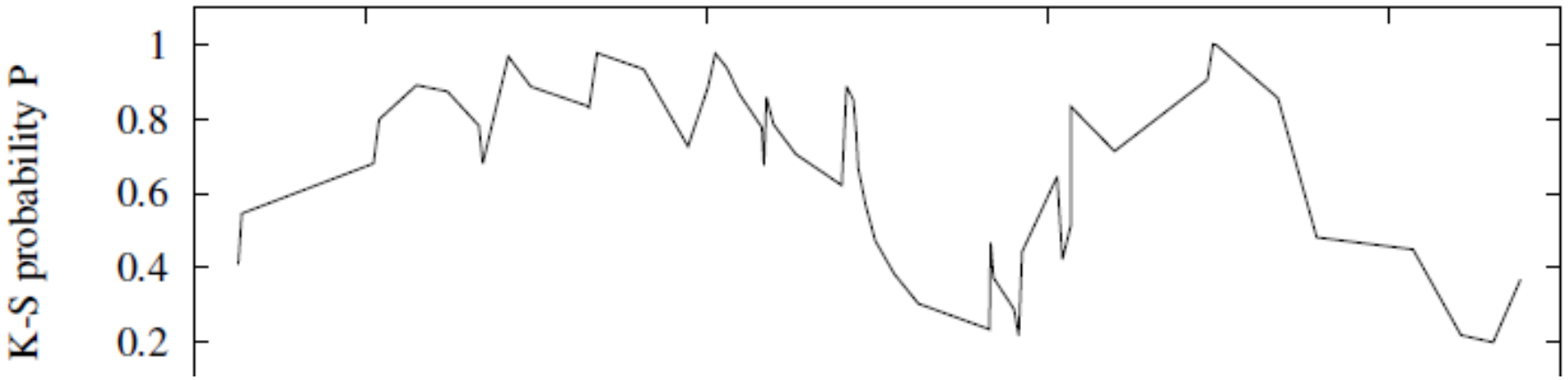
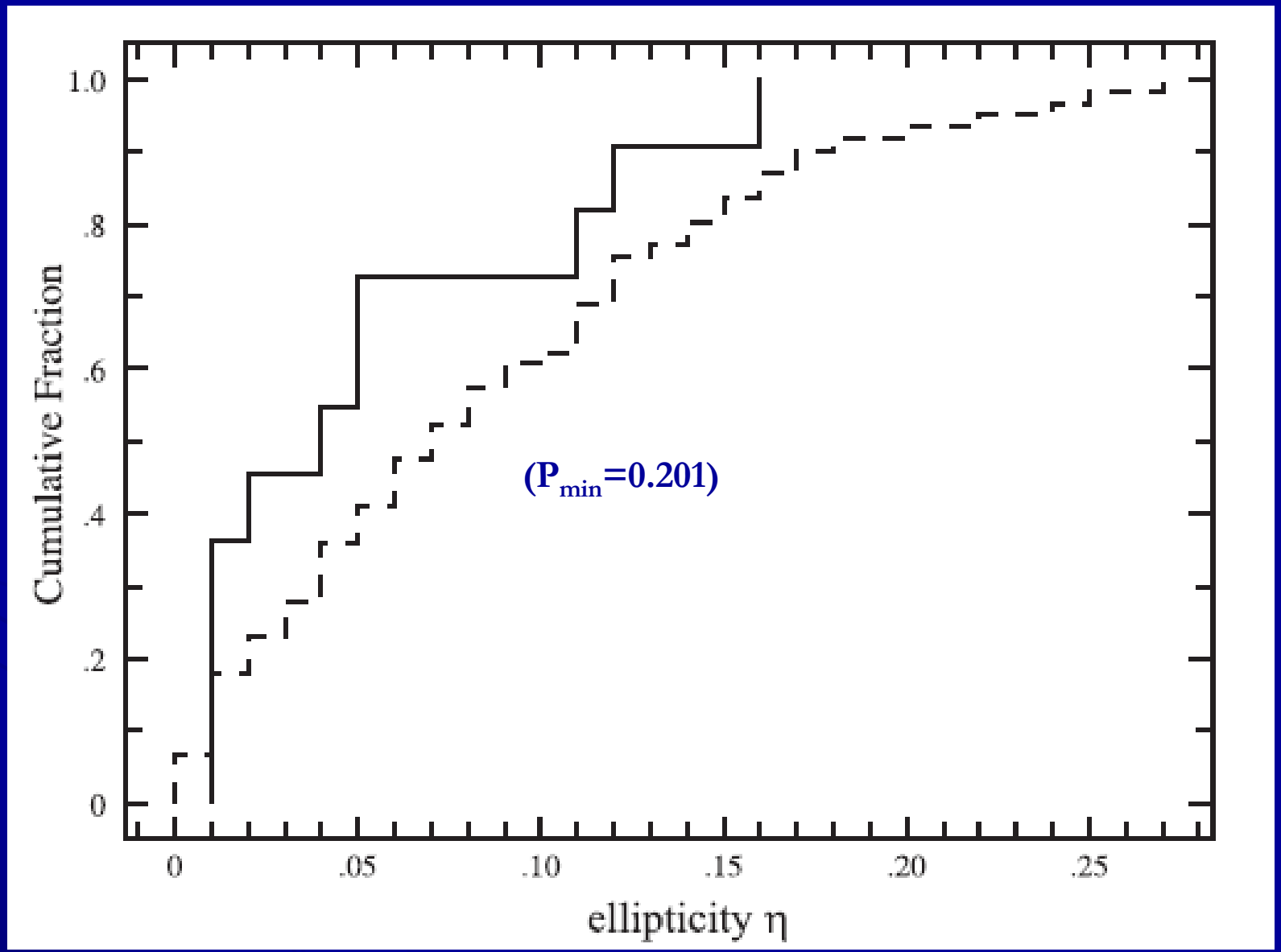


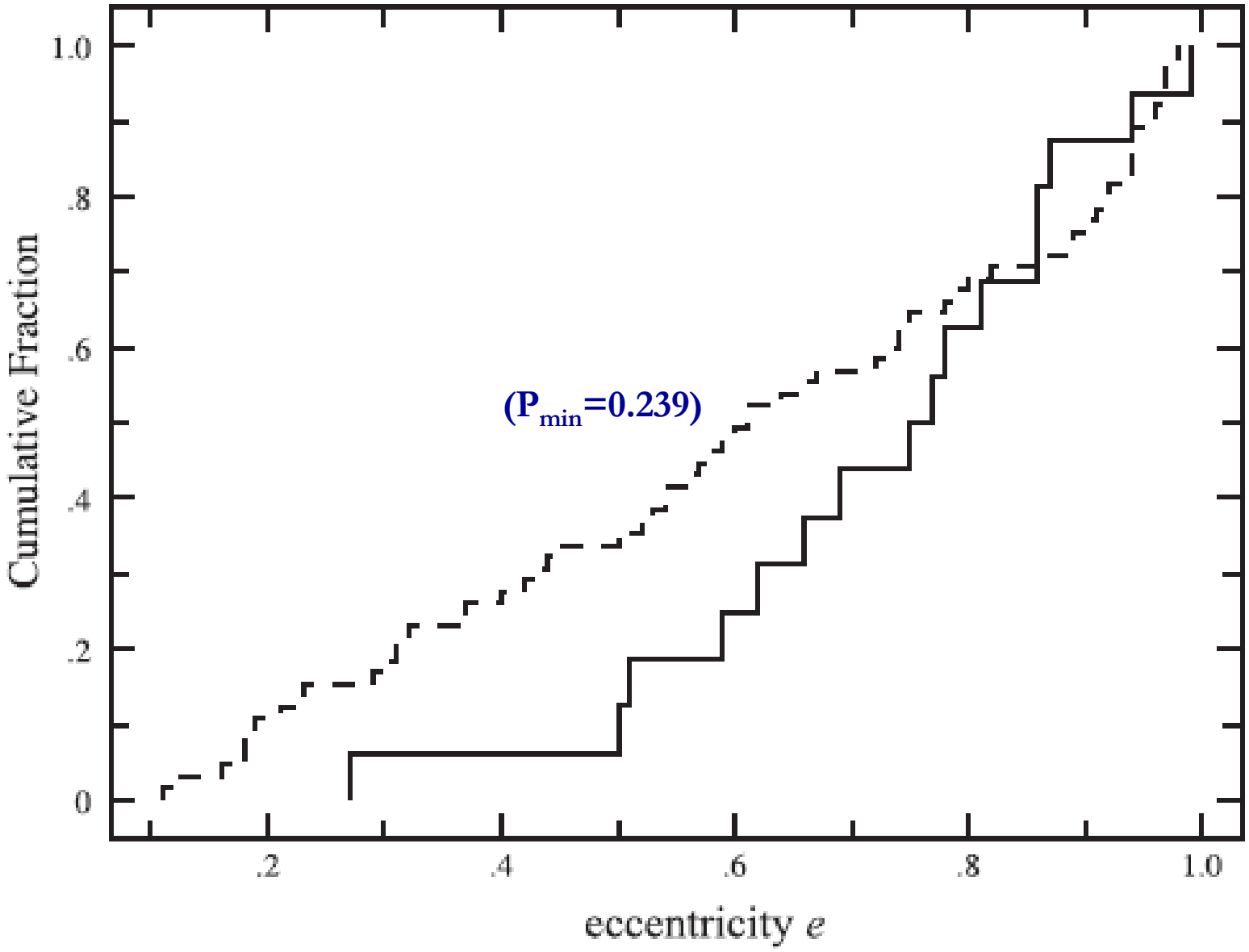
Таблица 6.2 – продължава от предходната страница

No.	$\log(Lx_{lim})$	$n(Lx<Lx_{lim})$	$\overline{\eta}(Lx<Lx_{lim})$	σ_η	$n(Lx\geq Lx_{lim})$	$\overline{\eta}(Lx\geq Lx_{lim})$	σ_η	D-stat.	K-S prob.
43	33.033	52	0.085	0.070	20	0.069	0.061	0.1577	0.833
44	33.097	53	0.084	0.069	19	0.070	0.062	0.1797	0.713
45	33.233	54	0.083	0.069	18	0.073	0.062	0.1481	0.905
46	33.241	55	0.081	0.069	17	0.078	0.061	0.0898	1.000
47	33.246	56	0.082	0.069	16	0.075	0.062	0.1071	0.998
48	33.336	57	0.083	0.069	15	0.069	0.059	0.1684	0.856
49	33.393	58	0.085	0.070	14	0.059	0.048	0.2389	0.482
50	33.534	59	0.085	0.070	13	0.057	0.049	0.2516	0.450
51	33.604	60	0.086	0.069	12	0.054	0.050	0.3167	0.220
52	33.651	61	0.085	0.069	11	0.054	0.053	0.3338	0.201
53	33.691	62	0.084	0.069	10	0.058	0.054	0.2968	0.369

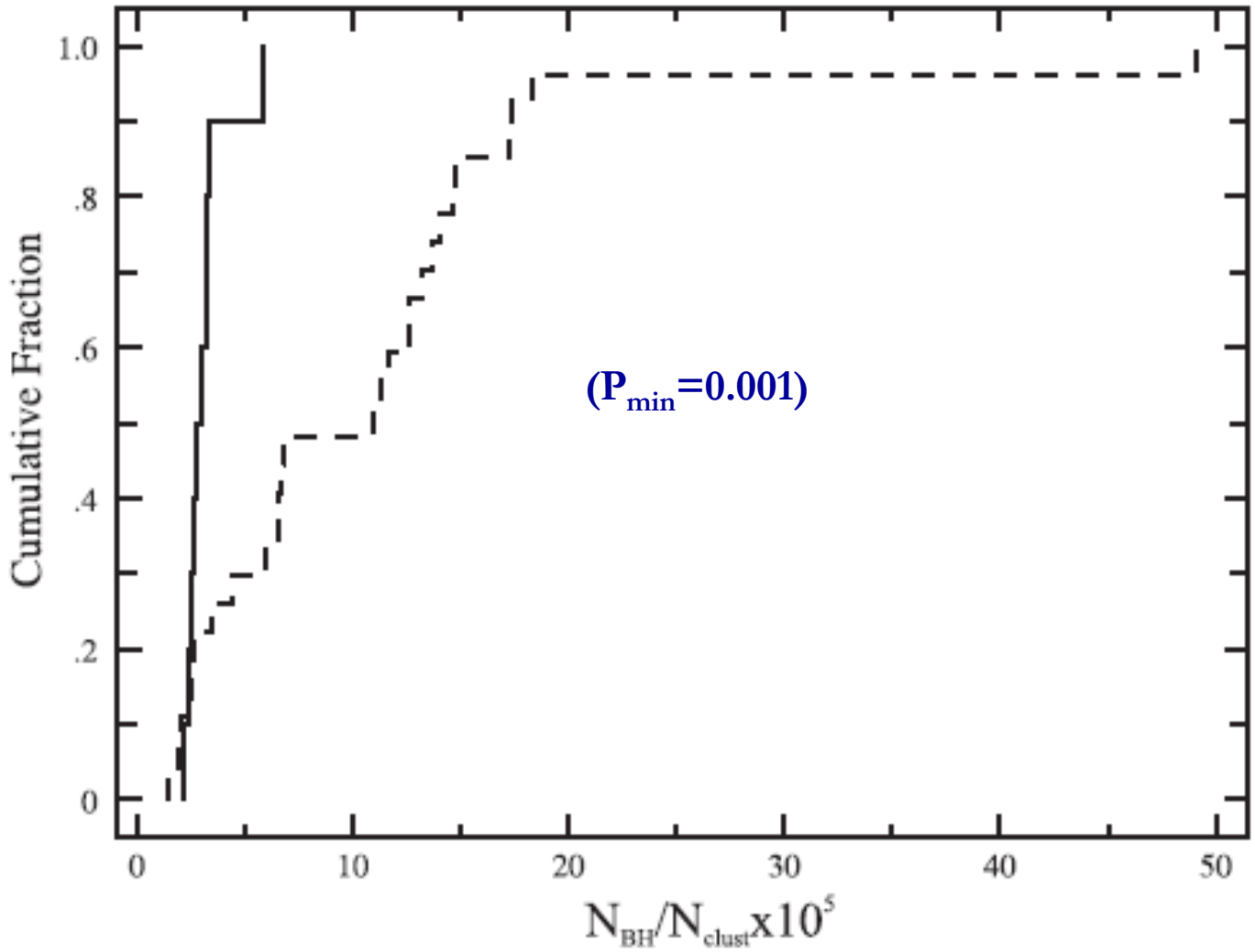
Results from the K-S test for ellipticity



Results from the K-S test for eccentricity



Results from the K-S test for the number of black holes



Results from the K-S test in tabular form

Parameter	n(Lx≥Lx_{lim})	n(Lx<Lx_{lim})	D-stat.	K-S prob.
ellipticity η	11	61	0.334	0.201
eccentricity e	16	65	0.276	0.239
$N_{BH}/N_{clust.}$	10	27	0.704	0.001

Conclusion - 1

- for 89 Galactic globular clusters (according to the catalog of Harris – 2010 edition) data about x-ray flows are collected from their individual sources in the scope of 2 r_c (the radius of the core);
- for 89 Galactic globular clusters the total x-ray luminosities are calculated and homogenized in the scope of 2 r_c and the function on x-ray luminosity is built;
- 3 pairs of samples are prepared for the parameters ellipticity (11 globular clusters with high and 61 globular clusters with low x-ray luminosity), eccentricity of the orbit (16 globular clusters with high and 65 globular clusters with low x-ray luminosity) and supposed number of the black holes with intermediate mass (10 globular clusters with high and 27 globular clusters with low x-ray luminosity);

Conclusion - 2

- the probability of both samples, for which there is an available parameter, is appreciated to be statistically different with the help of the Kolmogorov-Smirnov test. To be more precise, for the parameters ellipticity and eccentricity cannot be prove statistically significant difference ($P>0.2$). However, for the parameter number of black holes, the test result testifies to significant statistical difference ($P=0.01$), but the samples have limited statistical representativeness.
- There are available indications,that the globular clusters with higher x-ray luminosity everything distinguish with lower ellipticity, with higher eccentricity and smaller number of black holes with intermediate mass.

We would like to refer National RI Roadmap Project DO1-176/29.07.2022 with Ministry of Education and Science of the Republic of Bulgaria !!!

Thank you for your attention!