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TIME SERIES ANALYSIS OF AGNs

ANDJELKA KOVAČEVIĆ[1], LUKA Č. POPOVIĆ[2], ALLA I. SHAPOVALOVA[3]
and DRAGANA ILIĆ[1]

[1] *Department of astronomy, Faculty of Mathematics*
University of Belgrade, Serbia
E-mail: andjelka@matf.bg.ac.rs, dilic@matf.bg.ac.rs
[2] *Astronomical Observatory Belgrade, Serbia*
E-mail: lpopovic@aob.bg.ac.rs
[3] *Special Astrophysical Observatory of the Russian AS, Russia*
E-mail: ashap@sao.ru

Abstract. In the context of information and astroinformatics, we present results of time series analysis of some of well known type 1 Active Galactic Nuclei.

1. INTRODUCTION

Sixty years have been passed since Cygnus A was optical identified (Baade & Minkowski, 1954) as an extra-galactic source and the first powerful active galactic nucleus (AGN). Since then, powerful AGNs have been identified across the electromagnetic spectrum and in galaxies inhabiting both the local Universe up to z∼7 (Mortlock et al., 2011). Non-stellar character of AGNs has been widely accepted, since their spectra indicate a non-thermal source. The AGN's spectral energy density is consistent over most frequencies so it is too broad to originate from a radiating blackbody such as star.

To achieve extremely large observed luminosities ($> 10^{48}$ $\mathrm{erg\,s^{-1}}$), AGN energy source must be ∼100 times more efficient than nuclear fusion. Up to now, the release of gravitational potential energy from the accretion of material onto a supermassive black hole ($M > 10^6 M_\odot$) is the only known mechanism able to explain the observations (Lynden-Bell, 1969). Matter falling onto the black hole that possesses angular momentum could be accreted onto a disk, radiating energy from both frictional heating of layers of the accretion disk, or from the release of gravitational potential energy. Some of the material could be accelerated to relativistic speeds and ejected perpendicular to the accretion disk, forming the jets of radio-loud AGN. The exact mechanisms are still not known.

The classification tree of AGNs is obscured, since the distinctive characteristics of various sources mainly reflect historical differences in advances of technology of their discovery. Soon after the discovery of quasars (the most luminous AGNs) it

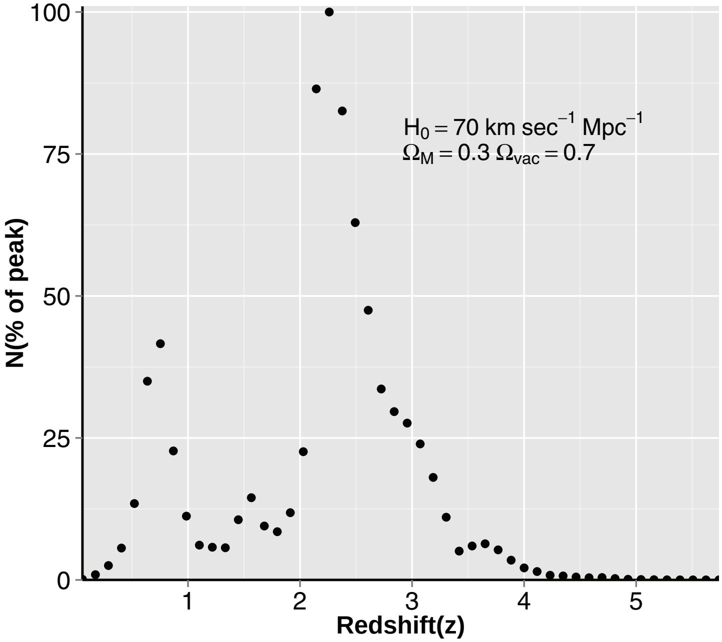


Figure 1: The SDSS-DR9 Quasar Catalog (DR9Q): Relative number of quasars (N- as a fraction of the peak value) per comoving volume element as a function of redshift z. Comoving volume element is calculated using astCalc procedure, the input cosmological parameters are given in the legend.

was evident that their space density reached peak at redshift $z \sim 2.3 - 2.5$ or at a look-back time of 78% of the age of the Universe (Fig. 1).

As emphasized by Bekenstein (2004), the General relativity sharpened the definition of black hole into a region of space rendered causally irrelevant to all its environment by gravity in the sense that no signal, by light, massive particles or whatever, can convey *information* about its nature and state to regions outside it. Using parallels with thermodynamics and information, where a black hole can be seen as a storage facility to hide information, Bekenstein (1973) proposed that the surface area of a black hole serves as a measure of its entropy, and it was refined by Hawking (1975). This relationship for an uncharged, non-rotating black hole is

$$S = \frac{kA}{4L_P^2} \tag{1}$$

where S is the entropy of black hole, A is the area of the event horizon of black hole, the k is Boltzmann constant and $L_P = \sqrt{\frac{G}{\hbar c^3}}$ is Planck length. If the Boltzmann constant is omitted the entropy has dimensionless form. While the surface area of the horizon of a black hole, measures the entropy of the black hole, the entropy is a measure of information I (or information loss),

$$S = k \log_2 I \tag{2}$$

So the Bekenstein-Hawking formula (BHF, (1)) relates the total information content of a region of space to the area of the surface encompassing that volume. Soon, Bekenstein (1981) sought to generalize his result by postulating that the information content of any physical system can never be larger one quarter of the area of its encompassing surface. Following this attempt, Gerard 't Hooft (1993) and Susskind (1995) suggested the so-called holographic principle, according to which the information content of the entire universe is captured by an enveloping surface that surrounds it. Beside this, the principle was generlized that the total information content of a region of space cannot exceed one quarter of the surface area that confines it.

Hence, the entropy or potential information that can be extracted from a configuration of matter within a volume is strictly limited by the extension of its bounding surface, whereas its ontological determination requires a higher degree of actual information. This defines how much information can be contained in a specified region of space, or conversely, the maximum amount of information required to perfectly describe a given physical system down to the quantum level. One can attribute this quantity to the data store (or the thermodynamic microstates) and call it amount of data in the system.

Here, we will recapitulate some of our results of AGNs time series investigations in the context of profound notion of information and astroinformatics as a new discipline. The detailed description of objects, data and statistical methods are given in Kovačević et al. 2014, unless otherwise specified.

This work is organized as follows: some preliminaries on relation between information and black hole mass is examined in the section *Information and black hole mass*; in the section *Discussion* we estimate entropy density of objects with masses similar to Arp 102B and 3C 390.3, as well as entropy of Arp 102B and 3C 390.3 itself. Also we demonstrate that probability structure function (PSF) of ZDCF curves of Arp 102B, 3C 390.3, NGC 5548 and NGC 4051 assigned these objects to different clusters. The section *Conclusion* summarizes our results.

2. INFORAMTION AND BLACK HOLE MASS

Until the mid-twentieth century, the dominant paradigm in both science and technology was that of energy- the laws of physics had been developed to understand the nature of energy and how it could be transformed and used. In the mid-twentieth century, began a new revolution of technology of information processing and computation.

Hartley (1928) was the first who turns the notion of information into scientific concept by means of making information measurable. The unit of information (the bit), is actually a pure -dimensionless number. Due to this, the information must be invariant to coordinate transformations (while the mass, velocity, diameters are not such invariants). Those entities-invariants of coordinate transformations are of great interest in natural sciences.

In the natural sciences the constants of physical laws have the certain number of bits defined by their values. On the other hand, we are facing many processes which change with time- and they are actually information flow (Harmuth, 1982). For example, in order for a planet in our solar system to follow its orbit, it must constantly receive information about the ratio mass-distance $\frac{m}{r}$, varying with time, of all the other bodies. Also, some particle in an experiment would not be able to follow the path through the modern instruments without the transfer of information about electromagnetic field. In the first case, it was used the metric field while in the second case, the electromagnetic field was used to explain the transfer of information.

Information is physical, this statement of Landauer (1996) has two complementary interpretations. First, information is registered and processed by physical systems. Second, all physical systems register and process information.

In principle, every physical process can be described in terms of interactions between particles that produce binary answers: yes or no, here or there, etc. Thus natural laws, governing the interactions and rearrangements of the constituents of the physical universe are perceived as the flipping of binary digits, as in a digital computer.

If one chooses to regard the universe as performing a computation, most of the elementary operations in that computation consists of protons, neutrons (and their constituent quarks and gluons), electrons and photons moving from place to place and interacting with each other according to the basic laws of physics. In other words, to the extent that most of the universe is performing a computation, it is computing its own dynamical evolution. We have already mentioned the link between physics and information established in BHF. For a spherically symmetrical black hole, Penrose (1989) suggested this surface area turns out to be proportional to the square of the mass of the black hole, and found that the entropy (information) of a black hole is proportional to the square of its mass

$$S = \frac{2\pi k G M^2}{\hbar c \ln 2} \tag{3}$$

where k is Boltzmann's constant, c is the speed of light, G is Newton's gravitational constant, and $\hbar$ is Planck's constant over 2π.

Almost parallel with this theoretical investigations, the methods for black hole mass determination has been developed.

Using dynamical methods to derive BH masses of AGNs have not been generally feasible, since AGNs are very distant objects and so bright that outshine the "test objects". Instead, their the most striking characteristics of rapid variability in all accessible energy bands is used.

Cherepashchuk and Lyutyi (1973) discovered time delay effect. The time delay ($\tau_{BLR} = R_{BLR}/c$) between the changes in the optical-ultraviolet continuum produced in the compact accretion disk and the emisiion line from the further broad line region (BLR) gas clouds is measured by spectroscopic monitoring. In order to determine BH masses in AGNs, a well accepted working hypothesis is that the gravitational field of a central object controls the motion of gas near the nucleus (Dibai 1984). So the mass of a black hole can be estimated with $M_{BH} \sim \frac{R_{BLR} V^2}{G}$ under assumption that the gas around a black hole is virialized. The V is the characteristic velocity of BLR gas at distance R_{BLR} from the center of a AGN (Peterson and Wandel 1999) and G is the gravitational constant.

Once having the estimate of the black hole mass, we are able to calculate the information content of such object.

3. DISCUSSION

3. 1. ARP 102B AND 3C 390.3: SMBH MASSES AND ENTROPY

Using recent measurements of the supermassive black hole (SMBH) mass function, Egan and Lineweaver (2010) found that SMBHs (particularly around $10^9 M_\odot$) are the largest contributor to the entropy of the observable universe, contributing at least an order of magnitude more entropy than previously estimated. So, the SMBH mass determination of AGNs has significant importance of estimating the total entropy budget of the whole Universe.

In Table 1, we present results of time series investigations of 2 type 1 AGNs out of 4 such objects used in our analysis. For these two objects, we were able to determine SMBH masses in their centers. Using these values, we estimated the number density of objects per Mpc^3 per logarithmic mass interval (i. e. the values of SMBH mass function) with masses similar to Arp 102B and 3C 390.3 as well as entropy density of such objects.

We use three parametric Shechter function

$$\frac{dn}{d\log_{10} M} = \phi_* \left(\frac{M}{M_*}\right)^{\alpha+1} \exp\left(1 - \frac{M}{M_*}\right) \tag{4}$$

from (Graham et al. (2007), and Egan and Lineweaver (2010) as a model of SMBH mass function in observable Universe (see Fig. 2 the left panel). Expected contribution of objects with masses similar to Arp 102B (point 1 on the left panel) is greater than contribution of objects with masses similar to 3C 390.3 (point 2 on the left panel).

The SMBH entropy density Egan and Lineweaver (2010)) is related to SMBH mass function as follows:

$$entden = \frac{4\pi G k}{c\hbar} \int M^2 \frac{dn}{d\log_{10}(M)} d\log_{10}(M) \tag{5}$$

The entropy density is depicted at right panel of Figure 2. The primary contributors of entropy density are objects around $10^9 M_\odot$. The contributions of objects with masses similar to Arp 102B (point 1 on the right panel) is slightly smaller than contributions of objects with masses similar to 3C 390.3 (point 2 on the right panel). Their uncertainties are obtained varying Arp 102B and 3C 390.3 (Table 1) SMBH masses with $0.1 \times 10^8 M_\odot$ and $0.1 \times 10^9 M_\odot$, respectively. Arp 102B SMBH mass gives more accurate entropy density prediction than 3C 390.3 SMBH mass. It means that model used for Arp 102B is better matching the theoretical SMBH entropy density.

Also, using Penrose formula (3), we calculated the entropies of Arp 102B and 3C 390.3 (the last column of Table 1). Assuming that single SMBHs inhabit almost all of the 10^{11} galactic cores in the visible Universe, and that the information content of such object is 1.7×10^{95} (average value of information content of our two object), we could obtain that total entropy contribution of SMBHs, in visible universe, is 1.7×10^{106}. These result is three order of magnitudes larger than predicted by Egan and Lineweaver (2010). The reason for the difference is that we used the average value ($1.1 \times 10^9 M_\odot$) of our two SMBH masses, while Egan and Lineweaver (2010), used mass function which peak is about $10^8 M_\odot$. This emphasize need of more accurate SMBH mass determination, in order to obtain much better estimate of SMBH mass function and better estimate of SMBH contribution to the over all entropy of the Universe. The increase of entropy of Universe has not yet been limited (e.g. by mentioned holographic bound), so this is the reason that dissipative processes are going on and that life exist.

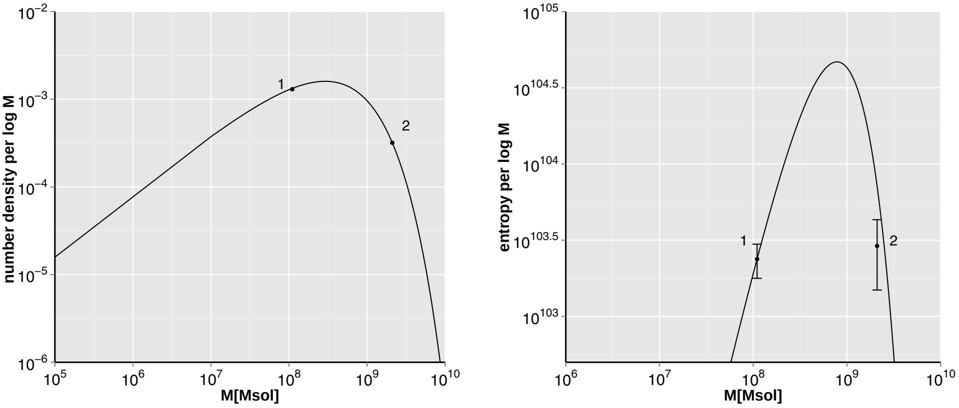


Figure 2: Left panel: SMBH mass function from Graham et al (2007) and Egan and Lineweaver (2010): the number of supermassive black holes per Mpc^3 per logarithmic mass interval. Ordinate of points 1 (0.0013) and 2 (0.000319) are values of SMBH mass function at our estimated masses of Arp 102B and 3C 390.3 respectively. Right panel: the mass distribution of SMBH entropies. Ordinate of points 1 and 2 are entropies densities of objects with masses similar to Arp 102B and 3C 390.3 (see Table 1).

Table 1: Arp 102B and 3C 390.3: time lag measurements and derived SMBH masses. The column ED: entropy density of objects with masses similar to Arp 102B and 3C 390.3. The colum E: entropies of SMBH of Arp102 B and 3C 390.3

Object	Continuum waveband (in Å)	Line	τ (days)	Method used	SMBH Mass $M_\odot$	ED	E
Arp 102B	cnt 6356-6406	Hα	$15^{24}_{-13.8}$,$24^{27.5}_{-18.8}$	ZDCF,SPEAR	1.1×10^8 Shapovalova et al. (2013)	$(2.378 \pm 0.6) \times 10^{103}$	9.22×10^{92}
	cnt 5200-5250	Hβ	$23^{64}_{-20.9}$,48^{57}_{-37}	ZDCF,SPEAR			
3C 390.3	cnt 5369-5399	Hα	$24^{95.8}_{-10.5}$,44^{49}_{-35}	ZDCF,SPEAR	2.1×10^9 Shapovalova et al. (2001)	$(7.15 \pm 1.4) \times 10^{103}$	3.4×10^{95}
	cnt 5369-5399	Hβ	95^{27}_{-48},77^{79}_{-75}	ZDCF,SPEAR			

3. 2. AN EXAMPLE OF CLUSTERING AGNS

Estimation of black hole masses could be done by time series analysis methods. There are a number of characterizing statistics based on the differences of all possible pairs of data points in a time series, e.g. different kind of cross correlation function (see Kovacevic at al (2014)). They have been frequently used since the time sampling of astronomical time series is often relatively sparse.

Usually, we compute a set of ~ 66 parameters and statistical measures for any of our objects, forming feature vectors in the parameter space of statistical measures. In such a way, our sparse heterogeneous light curves are translated into much more homogenized feature vectors in the statistical parameter space. Since, the classification is a primary feature of astronomical research, one can expect that using this statistical space could provide more insights in this problem.

As we mentioned earlier, the AGNs have obscured classification. Even the ZDCF curves are similar among different objects. As an example, the visualization of ZDCF analysis of 4 type 1 AGNs are given in Fig. 3.

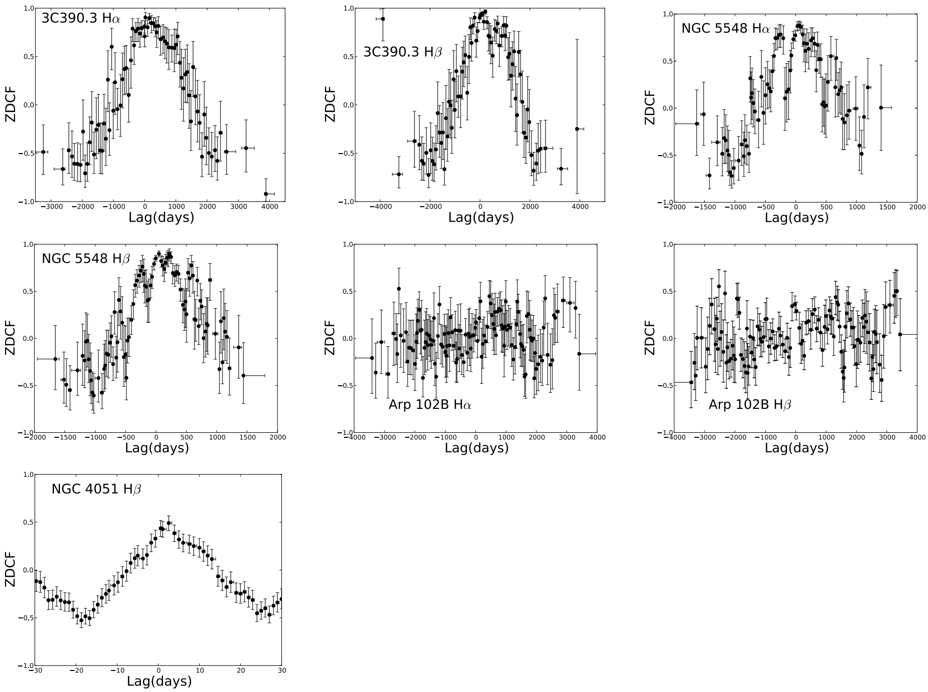
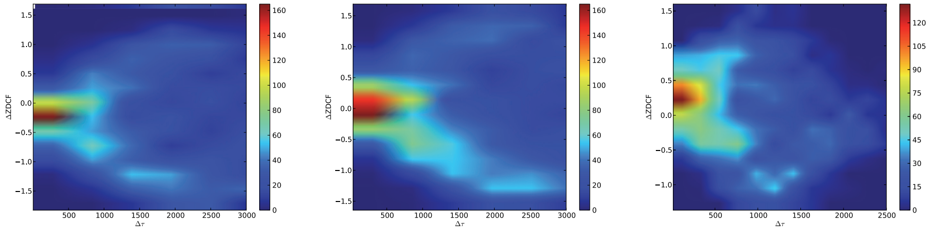


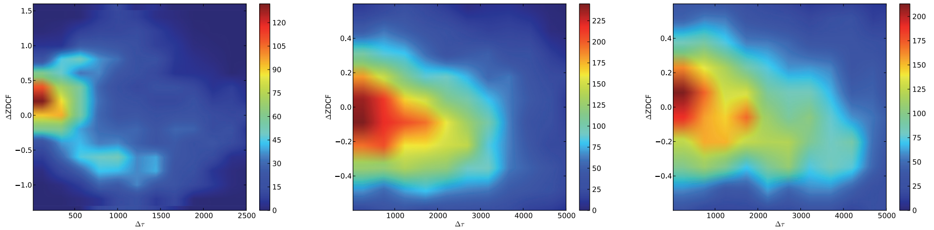
Figure 3: The ZDCF analysis: object and emission line denoted on each plot. The horizontal and vertical error bars correspond to 1σ uncertainties for a normal distribution.

We calculated 2D histograms of given ZDCF curves (see Fig. 4). These histograms can be viewed as probabilistic structure functions (PSF) of given ZDCF curves. According their shape, it is clear that 3C 390.3 and NGC 5548 have similar PSF of

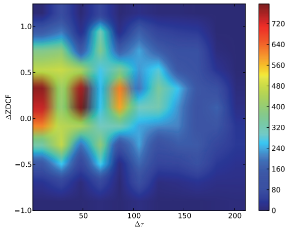
ZDCF curves, while Arp 102b and NGC 4051 have distinctive PSF . The measure of a similiarity and divergence between the class PSF of ZDCF curves of objects should be tested on larger sets of simulated curves. If it is approved, this could be efficient method for clustering objects.



3C 390.3 $H\alpha$ 3C 390.3 $H\beta$ NGC 5548 $H\alpha$



NGC 5548 $H\beta$ Arp 102B $H\alpha$ Arp 102B $H\beta$



NGC 4051 $H\beta$

Figure 4: 'Heatmaps' of ZDCF and lags of the object and emission line denoted below each panel. Colorbar indicates number of pairs (lag, ZDCF), the largest number of pairs are indicated by red color. Aspect ratio of each heatmap is different due to its dependance on the range of lags and ZDCF coefficients.

4. CONCLUSION

Here we present entropy density of SMBH with masses similar to our mass-estimates of Arp 102B and 3C 390.3. Entropy density based on Arp 102B mass is closer to theoretical entropy density curve than value based on 3C 390.3. This suggests that model of Arp 102B is better suited to theoretical entropy density than the 3C 390.3 model.

Also we calculate individual entropy content of Arp 102B and 3C 390.3 using Penrose formula and give prediction of entropy of the observable universe assuming the mean value of Arp 102B and 3C 390.3 masses. Obtained value is about 3 orders of magnitude higher than value obtained by Egen and Lineweaver (2010). The major dimension of astronomical research is the assignment of objects to classes, which is particularly accelerated with the development of astroinformatics. We demonstrate the utilization of features of statistical parameter space for clustering of 4 type 1 AGNs by means of PSF.

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