Searching for deterministic chaos in Kepler light curve of the Seyfert 1 AGN Zw229-015

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Abstract. We analyzed the optical light curve of Zw229-015 – a Kepler field disk-dominated AGN. We used the light curve, consisting of more than 13000 individual equally-spaced data points, aiming to search for deterministic (chaotic) signatures in it. The correlation integral method was applied for this purpose. We found no convincing evidence for the presence of a low-dimensional attractor, because perhaps the light curve was dominated by a characteristic timescale. We interpreted our results in terms of re-processing of high-energy central radiation into the optical band in the outer accretion disk.
Key words: galaxcies: AGN – chaos

Introduction

Zw229-015 is a nearby (z=0.028) Seyfert 1 active galactic nucleus (AGN) that happens to be located in the field of the Kepler satellite. Kepler observed continuously the same field for several years with a ∼30 min cadence, which allowed obtaining unprecedented in length, sampling and quality light curves (LC's) of the objects located there. As centered at Milky Way, however, this field contains not so many AGN and Zw229-015 is one of the brightest (V≃15.4). The combination of the observed relatively high variability (up to ∼40% on a monthly scale) with the high S/N of the LC allowed detailed studies of the optical variability properties of this object. Mushotzky et al. (2011) studied the power density spectrum (PDS) of the earliest available portions of the LC's of several Kepler field AGN, including Zw229-015, and found surprisingly steep slopes of about $\alpha \simeq -3$ ($PDS(f) \propto f^{\alpha}$), with a white noise saturation at $f > 0.25$ days^{-1}. These slopes are much steeper than the X-ray PDS's for other typical Sy 1's with $\alpha_{\rm x} = -1 \ldots -2$ (Edelson & Nandra 1999, Uttley et al. 2002) and seem to be inconsistent with the so called "Damped Random Walk, DRW" (Kelly et al. 2009), often used to model the AGN LC's (MacLeod et al. 2010), as the latter predicts roughly $\alpha \simeq -2$. Kasliwal et al. (2015a) used the structure function (SF) approach (see Graham et al. 2014, for an overview), which is technically equivalent to the PDS, and found somewhat less steep slopes for their sample of Kepler AGN, but still more than a half of them not being consistent with the DRW, including Zw229-015. Later on, Kasliwal et al. (2015b) proposed refined recalibration of the Kepler data, but concluded that the refinement does not alter their previous results. Edelson et al. (2014), on the other hand, studied the PDS of the entire available LC of Zw229-015 and found a break in the PDS slope at about 5 days. The authors associate this time either with the light-crossing time (perhaps slightly shorter), the dynamical time (perhaps slightly longer) or the thermal time (perhaps too long) at radial distances where the optical emission should be generated from the standard accretion disk. Another SF-based approach was employed by Chen & Wand (2015) to study the time asymmetry of the Kepler field AGN LC's, including the Zw229-015 one. They found no evidence for such an asymmetry for this and other objects, meaning that the AGN light curves, at least the optical ones, appear to be highly time-symmetric.

In this work we study the Kepler LC of Zw229-015 in order to search for the presence of deterministic chaos signatures in it. Since the accretion flow behavior is governed by a certain number of equations, its temporal evolution (including perhaps the light production) could in principle be not entirely stochastic, but chaotic (deterministic) instead. Such an approach was applied to the W2R 1926+42 LC, another Kepler-field object, where indeed no deterministic chaos was found (Bachev et al. 2015, hereafter Paper I). W2R 1926+42 is however a blazar, i.e. a jet-dominated object, where entirely different emitting mechanism is responsible for the light production. Finding deterministic chaos in a disk-dominated AGN, such as Zw229-015, may have important consequences for a better understanding of the accretion disk's physics and temporal evolution. So far, clues for a possible presence of chaotic signatures have been found in some X-ray LC's of disk-dominated (radio-quiet) AGN (Lehto et al. 1993; Gliozzi et al. 2002).

The optical LC of Zw229-015 was studied for the presence of deterministic chaos by Adegoke et al. (2017). They, however, used the non-recalibrated SAP flux (see the next section), which is known to produce apparently random offsets from segment to segment (at least). The difference in our approach is that we employ the entire LC of this object and make sure to smear out the possible random, yet significant deviations (Sect. 2).

The paper is organized as follows: The data and the methods used are described in Sect. 2. Sect. 3 shows the results, which are briefly discussed in Sect. 4. Our conclusions are in Sect. 5.

1 Data and methods

Zw229-015 was monitored by Kepler for about 3.3 years (quarters 4th to 17th) starting Dec. 19, 2009 with a sampling of about 30 min and a duty cycle of more than 95%. For this analysis we use the publicly available PDC-SAP flux, which means unfiltered light roughly between 4300 Å and 8900 Å after the calibration for instrument's internal errors. The instrument's photometric errors are within 0.2%, which is an unprecedented accuracy for such a long-term LC. A somewhat bigger problem, however, happens to be the recalibration of the raw data, e.g. Kasliwal et al. (2015b). To apply the Correlation Integral (CI) method (see below) we needed evenly spaced data. For this purpose, a linear interpolation had to be done between the adjacent segments where no data were available. In addition, every 5 points (i.e. $\sim$2.5 hours) of this interpolated LC were replaced by a single median-averaged value. This approach actually makes sense first, because the PDS appears to saturate anyway towards white noise for this object at time-scales shorter than $\sim$6 hours (see the Introduction) and second, because this way we can eliminate some random, yet significant (perhaps cosmicray induced) deviations. The final LC used for this analysis consisted of 13536 data points and is presented in Fig. 1 (see also Edelson et al. 2014).

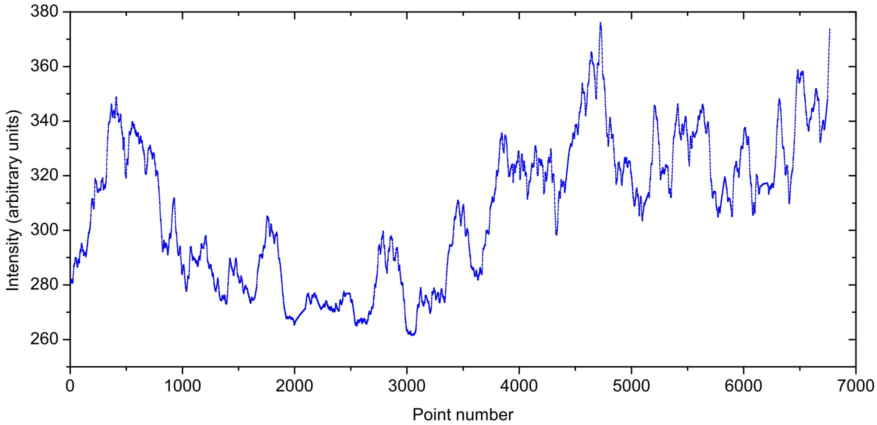

Fig. 1. The Kepler LC of Zw229-015 used for this analysis. Both – the count rate and the time are in arbitrary units, which is not of significance for our purposes

To search for deterministic chaos in the LC we used the CI method (Grassberger & Procaccia, 1983; see also Paper I and the references therein). Roughly speaking, this method searches for a spatial correlation between points (e.g. like the two-body distribution function), each point of which has been constructed using as coordinates the values of an n-number section of consecutive members of the LC from the entire dataset of length N¿n, where n can change from 1 to say about 10 (so called embedded dimensions). In other words, this approach will distinguish between points spread over the Earth surface (like cities, 2D distribution) and points uniformly spread throughout the Earth volume (3D distribution), which, $D = 2$, may not be so obvious if the cites' coordinates are somehow organized as a time series. Note that the 2D distribution of the cities will remain the same no matter how many dimensional space one considers the Earth to be embedded in, e.g. 3, 4, 5, etc. All technical details concerning the method are given in Paper I. The whole point here is that some dynamical systems can produce seemingly random time series but to be entirely deterministic in nature instead, i.e. being governed by a limited number of first-order nonlinear differential equations or variables. A famous example is the so-called Lorenz attractor (Lorenz, 1963), where a set of just 3 nonlinear differential equations, in a proper choice of the so called bifurcation parameter, produces an unpredictable and seemingly random (stochastic) dataset. The CI method here correctly identifies the number of the equations governing the system and well distinguishes between such a deterministic system from a random dataset generating one (Paper I). Therefore, finding signatures of an attractor (or in other words - deterministic chaos signatures) in our time series may reveal if the LC is governed by a (small, yet $N \geq 3$) number of equations (and estimate this number) or show that it is completely random, which may have significant implications on the physics of accretion or at least may help to better understand the disk-dominated AGN variability.

2 Results

The slope of the CI (Paper I and the references therein), will saturate at higher embedded dimensions in the presence of a low-dimensional attractor (Fig. 2 from Paper I). The embedded dimension that the CI slope saturates at, D, which is not necessarily a whole number for so called strange attractors, gives the number of the equations that govern the system, as $D < N \leq D + 1$. For instance, a sinusoidal signal will have D = 1 (which is understandable, provided that it is a 1D circle in the phase space) and there naturally N = 2 ($x' = y$; $y' = -x$). And again, this circle will remain 1D in the 3^+ D space as well. For the Lorenz attractor $D \simeq 2.06$ and $N = 3$. The results from our analysis are presented in Fig. 2.

As one may see the CI slope tends to saturate at D$\simeq$1, which basically means that a (quasi-) periodic signal perhaps governs the system (tests how different added signals or noises can destroy an attractor can be found in Lehto et al. 1993). It does not mean, however, that a distinct periodicity in PDS should necessarily be present (e.g. Fig. 4 from Edelson et al. 2014). Actually, no periodicity has been found or claimed in the PDS of the LC of Zw229-015. Perhaps the significant ($\Delta\alpha \simeq 2$) PDS slope change at about 5 days found (Edelson et al. 2014) is somehow related to the CI saturation at $D \simeq 1$ (see the next section).

Similar results were obtained from the surrogate LC, which was generated after phase randomization of the LC values with preservation of the original PDS (Schreiber & Schmitz 2000). A "true" attractor (where the saturation is not due to some PDS peculiarity) would be "destroyed" in terms of the CI slope saturation after such phase randomization (Paper I).

3 Discussion

Zw229-015 is a disk-dominated AGN, where almost all of the variable optical emission is generated within an accretion disk. Barth et al. (2011), based on their reverberation mapping campaign estimated the central black hole mass $M_{BH} \simeq 10^7$ $M_\odot$ and the Eddington ratio $L/L_{Edd} \simeq 0.05$. These are rather typical values for a standard thin disk to operate (Shakura & Sunyaev 1973). The main driver of the accretion disk luminosity is in principle the accretion rate. If the gas supply at the outer disk radius changes in some random (unpredictable) manner, so would the disk luminosity do and the LC will be random (stochastic). However, the viscous time (the characteristic time of the accretion rate changes) is way too long to account for

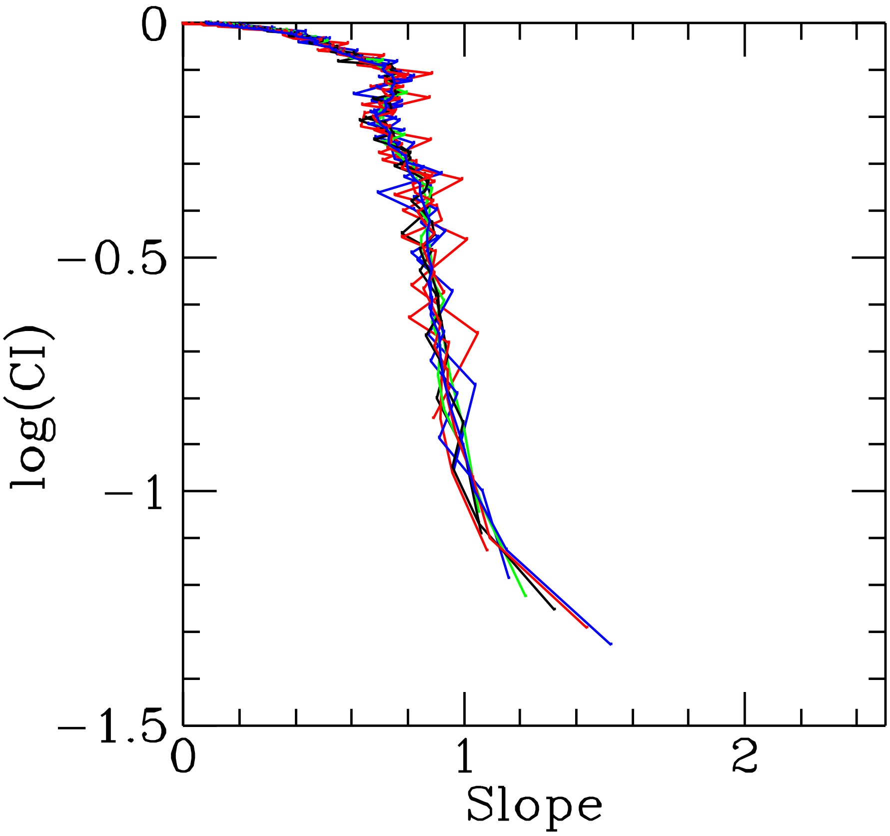

Fig. 2. The correlation integral vs. its slope of the Zw229-015 LC for the first 10 embedded dimensions. The CI appears to saturate at D≃1 for all embedded dimensions. Compare this graph with the same for random noise and Lorenz attractor (Fig. 2 from Paper I)

the observed fast AGN variability. Therefore, the LC should be governed by the local dynamics of the disk, perhaps rather close to the black hole to account for the fast variations. If so, a limited number of equations would be involved in modeling the (deterministic) variability process and the CI will in principle saturate at some (small enough) D. Still, D is not expected to saturate at about 1, as our results show.

Another possibility to account for the observed optical variations is to invoke reprocessing of high-energy radiation (UV, X-ray) from the center into optical photons from the cooler portions of the disk (e.g. Bachev et al. 2009, and the references therein). If this is the case, even if the reprocessed radiation changes are deterministic in nature, the disk transfer function will smear them and the optical output may not already reproduce the true CI slope correctly. Instead, having in mind that a characteristic time-scale (the disk light-crossing time) will play a significant role in the optical LC, one can indeed expect D≃1.

Thus our results seem to favor reprocessing to account for the observed LC. However, one is to bear in mind two caveats that can both in principle alter our results and conclusions:

1. The Kepler LC data may still require some (fine) recalibration (Kasliwal et al. 2015b) due to pure instrumental effects.
2. The Kepler optical range contains emission lines (mostly hydrogen), which are variable and are delayed behind the continuum. Interestingly enough, the slope change at ∼5 days is very close to the Broad Line Region radius (∼4 light days; Barth et al. 2011).

Summary

We studied the optical light curve of a Kepler-field AGN: Zw229-015, analyzing more than 13000 individual points. Our goal was to search for deterministic signatures (chaos) in the LC. No such was identified, yet the Correlation Integral appears to saturate at $D \simeq 1$. We interpret this result as a dominance of a characteristic time-scale over the LC, which is perhaps an indication for reprocessing as the main driver of the optical variability.

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