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ADDITIONAL SUPPORT FOR RELATIVE WAVELENGTH INDEPENDENCE OF IR LAGS IN NGC 4151 OVER THE PAST DECADE

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ABSTRACT. We present results of a study of the correlation between the infrared (*JHKL*) and optical (*B*) fluxes of the nucleus of the Seyfert galaxy NGC 4151 for the years 2010–2015 using our own data (partially published) in combination with published data [1, 2, 3, 4]. We find similar lags for each of the *HKL* passbands relative to the optical of 37 ± 3 days. The lags are the same to within the accuracy of measurement. We do not confirm a significant decrease in the lag for *HKL* in 2013–2014 previously reported by Schnülle et al. [4], but we find that the lag of the short-lag component of *J* increased. We discuss our results within the framework of the standard model, where the variable infrared radiation is mainly due to the thermal re-emission of short-wave radiation by dust clouds close to a variable central source. There is also some contribution to the IR emission from the accretion disk, and this contribution increases with decreasing wavelength. The variability in *J* and *K* is not entirely simultaneous, which may be due to the differing contributions of the radiation from the accretion disk in these bands. The absence of strong wavelength-dependent changes in infrared lag across the *HKL* passbands can be explained by having the dust clouds during 2010–2015 be located beyond the sublimation radius. The relative wavelength independence of the infrared lags is also consistent with the hollow bi-conical outflow model of Oknyansky et al. [5].

Key words: Galsxies – active galaxies: individual: NGC 4151

АБСТРАКТ. Дана робота є продовженням серії наших досліджень кореляції інфрачервоної і оптичної змінності в NGC4151, а також змінності величин ІЧ-запізнювання і їх залежності від довжини хвилі. У цих роботах було знайдено, що величина запізнювання у фільтрі *K* різна в різних станах активного ядра, а також що відношення величин запізнювань у фільтрах *L* і *K* значно міняється в межах 1-3. Докладний історичний огляд і обговорення отриманих результатів представлені в наших попередніх публікаціях. У даній роботі ми на повнішому наглядовому матеріалі, застосовуючи два незалежні методи аналізу, підтвердили відносну незалежність ІЧ-запізнювань від довжини хвилі протягом 2010-2015 рр.

Досліджено кореляцію між інфрачервоним (JHKL) і оптичним (B) потоками змінного ядра сейфертівської галактики NGC 4151, використовуючи наші дані (частково опубліковані), а також опубліковані дані [1, 2, 3, 4] за 2010–2015 рр. Знайдені запізнювання змінності потоку в HKL щодо оптичних варіацій збігаються в межах точності вимірювань і рівні приблизно 37±3 дням. Ми не підтвердили значне зменшення запізнення для HKL в 2013–2014 рр., яке виявили Шнулле і ін. [4], але помітили, що компонент з коротким запізненням в J посилився.

Ми обговорюємо наші результати в рамках стандартної моделі, де змінна інфрачервоного випромінювання пов’язана головним чином з тепловим перевипроміненням короткохвильового випромінювання пиловими хмарами, близькими до змінного центрального джерела. Існує також певний внесок в ІЧ-емісію від аккреційного диска, причому цей внесок збільшується із зменшенням довжини хвилі. Змінність в J і K відбувається не зовсім синхронно, що, можливо, повязано з різним внеском випромінювання аккреційного диска в цих фільтрах. Відсутність змін ІЧ-запізнення з довжиною хвилі (HKL) можна пояснити тим, що пилові хмари протягом 2010–2015 рр. були локалізовані далі, ніж радіус області можливої сублімації. Відносна незалежність ІЧ-запізнення від довжини хвилі також узгоджується з моделлю порожнинного біконічного витоку пилових хмар [5]. Створення самоузгодженої моделі ІЧ-випромінювання поблизу активного ядра виходить за рамки даної статті.

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1. Introduction

The nucleus of NGC 4151 is one of the most studied active galactic nuclei (AGNs), due to its brightness and significant variability at all frequencies, with the exception of radio frequencies. It has been intensively studied since the discovery of variability in 1967 [6]. The historical optical light curves from photographic plates dating back to 1906 [7, 8, 9, 10] and subsequent photoelectric observations (in particular observations by V. M. Lyutyi) are among the longest for any AGN.

There are a number of IR and optical photoelectric observations dating back before 1967 (see references in [11, 12, 9]). The variability of NGC 4151 was discovered back in 1958 from photoelectric observations, but these results were published only 10 years later [13], when the variability of the object was already established. NGC 4151, had changed its type from Sy1 to Sy2 [14, 15, 16]. It then returned, after a while, to being a Sy1 [17]. That was one of the first discovered so-colled "changing look" cases with AGNs. At present, several dozen such cases of "changing-look" AGNs (CL AGNs) have been recognized, which allows us to conclude that this is not just a one-time phenomenon, but is relatively common. Obviously, the orientation of the object cannot change so quickly and thus CL AGNs are a serious problem for the simple orientation-unification model (e.g. [18]). The unification model is based on the concept of the existence of a so-called "dusty torus", which, for viewing angles far from the axis of symmetry, obscures the broad line region (BLR) from the observer. The IR radiation of AGNs is dominated by thermal emission of dust heated by radiation from the inner regions of the accretion disc – emission that is energetically dominated by the extreme UV. The shape and structure of the torus is uncertain. Although it is commonly depicted in cartoons as being like a doughnut. Spatially-resolution IR observations of a number of AGNs show that dust clouds predominantly emitting in the mid-IR and far-IR range are not concentrated in the plane of the galaxy or of the accretion disc, as expected, but in polar regions [19, 20, 21, 22]. The main method for studying the unresolved structure of the emission from warm dust is reverberation mapping using IR and optical (UV) variability data. NGC 4151 was the first AGN for which such a lag was assumed on the basis of a visual analysis of light curves [23]. This lag was interpreted as a consequence of the spatial remoteness of the dust heated by the variable radiation from the central source. The lag was later measured using the standard cross-correlation analysis of series of observations [11, 24]. The first measurement of the lag in variability in the K band with respect to the optical in NGC 4151 gave a lag of about 18 days [11]. The lag was longer, about 26 days, for the L band from the same data Oknyansky2001. The IR lag for NGC 4151 varies with the level of luminosity of the central source, but with a delay of some years [25, 26]. The change in the lag can occur as a result of sublimation and dust recovery processes with changes in the level of the UV radiation of the nucleus. At present, such studies have been carried out for several dozen AGNs. Of great interest is the study of the dependence of the magnitude of the lag on the wavelength in the infrared range. For NGC 4151, in our first IR reverberation papers [24, 27, 28] it was noted that the lag in the longer-wavelength L band was significantly greater than the lag in the shorter wavelength K band. After the outburst of the nucleus in 1996, the IR lag significantly increased and, interestingly, the lags in the K and L bands were identical to within the limits of measurement accuracy [29]. In our more recent papers [30, 31] we again found that the lags in all IR bands of $JHKL$ were the same to within the accuracy of the measurements. Our analysis of the published photometric data for a number of other AGNs has shown that this relative independence of lags with IR wavelength is more the rule than the exception [30, 31]. We suggested that a significant increase in IR lag with wavelength can be observed during a period of significant growth of the luminosity of the central source, when dust sublimation occurs and the lag value increases. Because of the delay of several years in changes of the size of the lags, an increase in the magnitude of infrared lags with a wavelength can be observed after a few years after a major outburst. A straight-forward explanation would be that the dust clouds are located beyond the region of possible dust sublimation at the current luminosity level. Obviously, for most objects this situation is realized, when a major outburst occurred in the past and not in the time interval being studied. The possibility of determining cosmological constants based on the lag of infrared variability was first mentioned by [32] and was independently proposed and first implemented by [33, 27]. In recent publications of [34, 35, 36, 37], this method is considered in detail and practically applied (see also the discussion in [31]). Our discovery of the relative independence of the infrared lag from the wavelength for most AGNs is important in the practical application of this method, since it reduces the problem of a change in lag because of the shift in the rest-frame wavelengths of AGNs as a function of the redshift (for small $z \leq 0.2$). The application of this method to determine the distance to NGC 4151 has shown that this AGN is located at a significantly larger distance than previously thought [35]. The present paper is a continuation of our study of the lags of the IR passbands with respect to the optical in NGC 4151. We present results based on new monitoring in the $JHKL$ bands combined with optical photoelectric and CCD photometry for the period 2010–2015. For a detailed review of the research and a description of the observational methods and data analysis the reader is referred to [30]. In addition to our own observations we make use of IR and optical data published of [4]. The combination of the data sets helps to make the light curves more complete and hence gives a more reliable determination of the infrared lags. Lags are determined for the time series using our MCCF code as discussed in previous papers in this series. We also use the JAVELIN - Monte Carlo Markov Chain method of [38].

2. Observational data

The method of IR observations in $JHKL$ bands has been described in detail in our previous papers (see, for example, [39]). In the present study, we use our observations only for the 2010–2015 interval. Observations up to 2011 have been published in tabular form in Taranova and Shenavrin (2013), and observations up to 2015 are available on-line in an open access archive at *http : http : //www.sai.msu.ru/basa/inf.html*. We have already analyzed data from 2008–2013 in an earlier papers [30, 31]. Similarly we add here our new observations for 2013–2015, and also combined them with the published IR and optical data of Schnülle et al. [3, 4]. Most of the infrared observations have an accuracy of not worse than 1–2%. Compared to our earlier papers, the accuracy of our IR measurements improved during the interval being studied because of a number of upgrades of the equipment. In rare cases, the measurement errors were greater, but for further analysis we use only measurements with errors of no worse than 7%. In total, for the period 2010–2015, the average numbers of measurements per night in the J, H, K and L bands were 66, 54, 54, 66 respectively. Our data in JHK bands were supplemented by measurements of Schnülle et al. for 29 dates for 2010-2014. We reduced their data to our system. The method of optical photoelectric observations remained the same as that used by V.M. Lyutyi up to 2008 (see [24], but additional CCD measurements were used from a 60-cm telescope at the Southern Station of the SAI (see description in [40]). Since there are no U band CCD measurements, we used the data in the band B to construct a composite optical light curve. The CCD observations were reduced to a system of photoelectric measurements with a 27 arcsec aperture. As in our previous papers (see [5, 30, 31]) B-band data were supplemented with published CCD B-band measurements of Roberts and Rumstey [1] and 17 nights from Guo et al.[2]. In addition, we used 29 nights of optical measurements of Schnülle et al. [3, 4] in the red z band (29 dates) which were also reduced to our system B. Thus, all optical and infrared data are combined into one system. The formal accuracy of photoelectric measurements is generally not worse than 1–2%, but systematic differences between the measurements obtained on different instruments are possible. According to our estimates, these errors do not exceed 10% in the combined B-band light curve constructed for the 197 dates of the B value. The combined light curves NGC 4151 for 2010–2015 for $JHKL$ and B are presented in Fig.1. As it can be seen in Fig.1, variations in the brightness in the $JHKL$ bands occurred almost synchronously, without any noticeable differences or shifts. There are fewer points in the L band, since Schnülle et al. have no observations in this band. In the changes there are rapid variations (with a characteristic time of tens of days) and a long-term trend (with a characteristic time of several years or more) with a maximum at the beginning of the time period. The optical light curve also exhibits rapid and slow changes with the same characteristic times, and the slow trend is more noticeable than in the IR light curves. In addition, rapid changes of a small amplitude with a characteristic time on the order of several days are noticeable in the optical variability.

3. Methodology of cross-correlation analysis

Cross-correlation analysis of astronomical time series presents difficulties because the time series are often unevenly sampled. To analyze the series, we applied our MCCF code, which is an upgrade of the method of Gaskell and Sparke [41]. The methodology of our analysis has not changed, and is described in detail in previous papers (see e.g. [30, 31, 42]). In the MCCF method, we strive to introduce a minimum number of arbitrary parameters, and also significantly reduce the contribution made by interpolation errors. A detailed discussion of other methods of cross-correlation analysis of non-uniform series, and their comparison with the MCCF method, was carried out in our previous papers [30, 31, 42].

We also carried out an analysis of the time series using the JAVELIN Monte Carlo Markov chain code of Zu et al. [43, 38]. Further details and links can be found in [42]. The JAVELIN method is not a very common method of cross-correlation analysis. In this method, the light curves are simulated 10,000 times on the basis of assumptions about the properties of the AGN variability which is assumed to be a damped random walk (see [44], and then lags are found for each pair of these simulated light curves. A histogram is constructed of the lags thus found, which is used to find the optimal lag and its error (see, for example, [45, 43, 38]. Of course, this method has similar problems as any method using interpolation and extrapolation of the time series. Nevertheless, this method has been used recently in some studies and it usually yields similar results as other methods. We decided to use this method as an additional check of our results given by the MCCF method, and without any changes in the author's code.

To estimate the errors in the lags derived by the MCCF, we applied the same Monte Carlo procedure as before [24, 30, 31]. Our estimates of the errors in the lags gave a value of about 3 days. The histograms obtained in the JAVELIN method can be used to estimate the optimal lags (JAVELIN) and their mean–square errors (see details, e.g., [45, 38]).

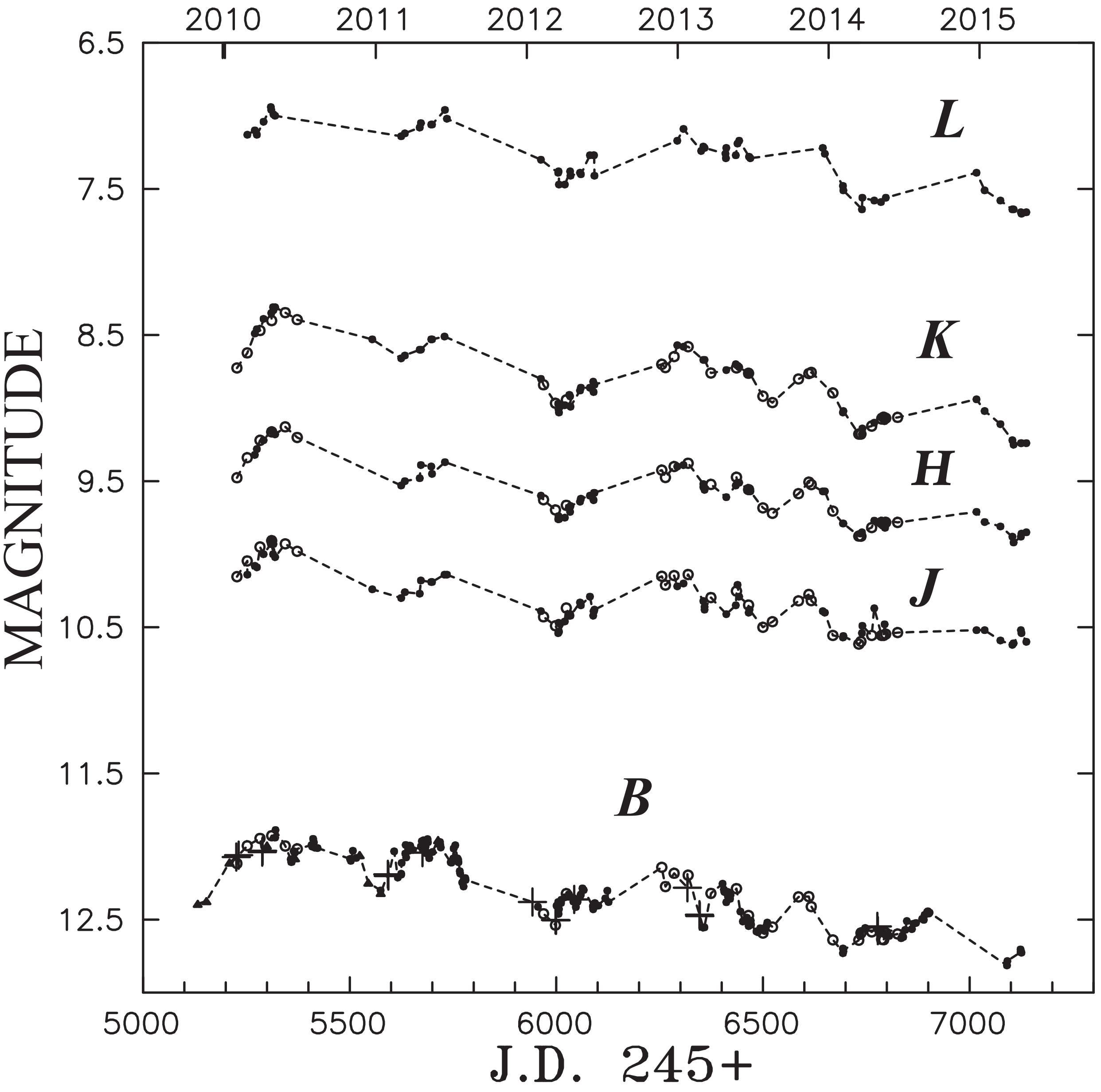

Figure 1: Combined light curves in IR bands $JHKL$ and optical B in 2010–2015. In IR light curves: filled circles - our data, open circles - data of Schnülle et al. ([3, 4]). In the light curve B: the points are our Crimean photoelectric and CCD measurements, the triangles are the reduced data of Roberts and Rumstey [1], the crosses are the reduced dots by Guo et al. [2], and the open circles are the reduced data of Schnülle et al.

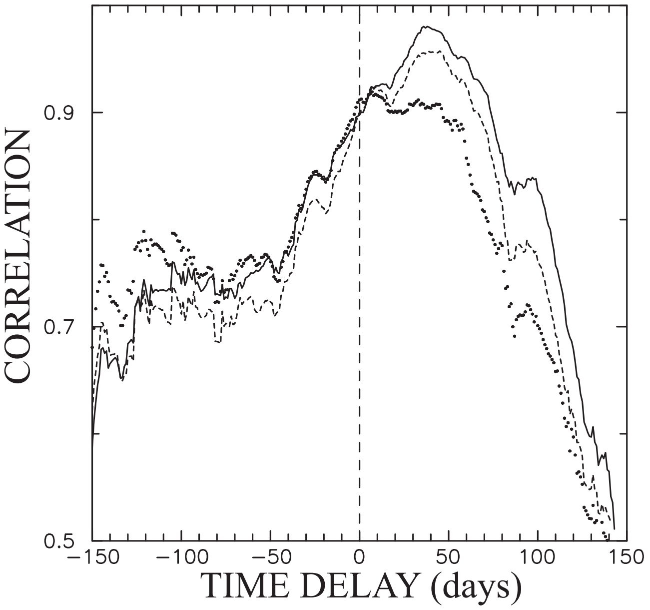

Figure 2: Cross-correlation functions for K (solid line), H (dashed lines), J (points) and B in the interval 2010–2015. The vertical dashed line indicates zero lag.

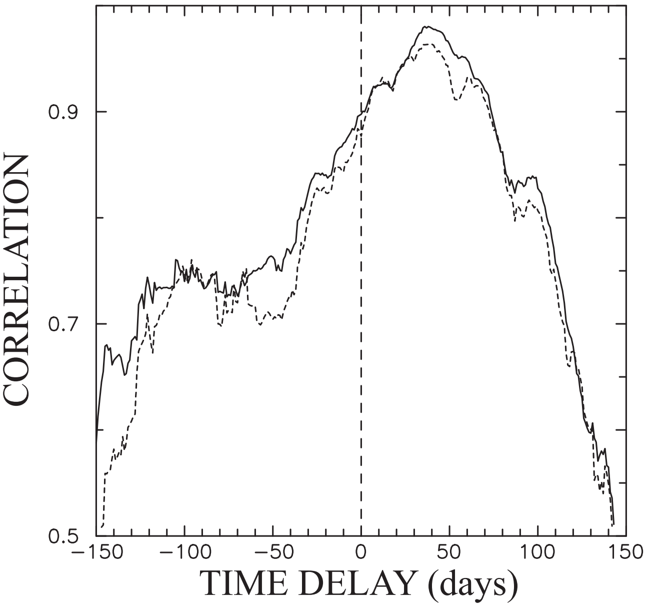

Figure 3: Cross-correlation functions for L (dashed lines), K (solid line) and B in the interval 2010–2015. The vertical dashed line indicates zero lag.

4. Cross-correlation of light curves

We have got cross-correlation functions of MCCF for the combined light curve in B and the variability in the $JHKL$ bands in the periods 2010–2015 and for 2013-2014 (Fig.2). Also we have made reverberation mapping with the JAVELIN method for the same data (not shown). Both methods give approximately the same results. For all IR pathbands most probable delay relative to B was found 37 ± 3 days. The magnitude of the lag of the variability at K relative to the optical remained almost the same as we found for the interval 2008–2013. Also, as in our earlier paper, the lag, within a measurement accuracy of ± 3 days is practically independent of the wavelength. But at the same time, the form of cross-correlation functions in the region near zero lag is noticeably different. One can notice that the secondary maximum and its significance fall as one goes to increasingly longer wavelength bands from J to L. For J, this maximum is about 4-6 days. This maximum is possibly associated with the variability of the accretion disc in the infrared. The delay for K and L (which are less depend for the AD radiation) were found about the same (see Fig.3). Our analysis did not confirm the result of Schnülle et al. [4] that there was decrease in the lag in 2012-2014 interval for the bands K and H, but for the band J the lag became noticeably smaller.

5. Conclussion

This paper is a continuation of our series of studies on the correlation between infrared and optical variability in NGC 4151, as well as the variability of the IR lag values and their dependence on the wavelength [11, 24, 29, 25, 30, 31]. In these studies we found that the delay in the K band is different in different activity states of the AGN, and also that the ratio of the lag values in the bands L and K varies considerably in the range 1-3. The results obtained in these studies were independently partially confirmed in other investigations [46, 26, 3, 47]. A detailed historical review and discussion of the obtained results was carried out in a our previous paper [30]. In the present paper, using more complete observational material and using two independent methods of analysis, we confirmed the relative independence of infrared lags from the wavelength during 2010–2015. Taking into account our past investigations we can say that the IR time delays relative to the optical variations were wavelengths independent at list during past decade.

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