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Nuclear Activity of the Seyfert Galaxy NGC 7469 in 1990–2006: Observations from the Mt. Maidanak Observatory

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Abstract—We present the results of $UBVRI$ observations of the nucleus of the Seyfert 1 galaxy NGC 7469 performed in 1990–2006 at the Mt. Maidanak Observatory of the Ulug Beg Astronomical Institute in Uzbekistan. Light curves for various apertures are plotted for all the filters. Our analysis of these light curves indicates the presence of short-time-scale (from several days to several weeks) and long-term (∼8–9 years) variability of the nucleus. The character of the brightness variations in all the optical filters is the same, with the relative amplitude of the variations decreasing from U to V, but being higher in R than in V. A comparison with earlier observations (prior to 1990) indicates an increase of the time scale for the long-term variability, from three to six years to eight to nine years, providing evidence for changing emission conditions in the accretion disk. We present the results of a statistical analysis of the light curves and an analysis of the color characteristics during different activity periods. Color-index measurements using various apertures demonstrate that the color becomes bluer towards the galaxy nucleus.

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1. INTRODUCTION

Astrophysicists have long been investigated the variability of active galactic nuclei (AGNs): such studies help to understand the nature of and explain the diversity of these remarkable objects, whose activity is due not to stars, but to a strong energy release in a relatively small central region of the galaxy ($R < 1$ pc). Galaxies with especially bright nuclei were discovered by Seyfert in 1943, and are called Seyfert galaxies [1]. The main feature of a Seyfert galaxy is activity of its central region, observed as a compact, variable object, and the presence of an ultraviolet excess in the galaxy's central region. A considerable amount of observational material has been accumulated on Seyfert galaxies, and thousands of papers have been written; however, it remains of interest to systematically supplement existing databases with new observations and to search for regularities and characteristic features of the radiation at all wavelengths, which can be used to test theoretical models for the central energy source.

The Seyfert 1 galaxy NGC 7469 (Arp 298 = MCG 1-58-25) is a spiral SBa galaxy slightly inclined to the line of sight. Its coordinates are RA = $23^h03^m15.75^s$, Dec = $+08°52'25.9''$ (2000.0). The distance to the galaxy is $D = 68$ Mpc for $H_0 = 75$ km s^{-1} Mpc^{-1}, and its redshift is $z = 0.01639$. Star-formation regions form a ring around the central part of the galaxy. Another ring of star-formation regions is visible in the infrared 1.5″ from the galaxy's nucleus. The central region of NGC 7469 exhibits variability in the ultraviolet, optical, and infrared, as well as in spectral lines. NGC 7469 is a weak radio source, and behaved like a radio supernova between 2000 and 2002 [2, 3].

Optical photometry of the nucleus of NGC 7469 was performed by Doroshenko et al. [4] between 1967 and 1987, by Merkulova [5] in 1990–1998, and by Sergeev et al. [6] in 2002–2003, at the Crimean Astrophysical Observatory and the Crimean Laboratory of the Sternberg Astronomical Institute. The AGN Watch international project organized in the mid-1990s [7] has yielded results published in many papers on variability of AGNs, including optical variations of NGC 7469 (e.g., [8–10]; rapid variability, see [11–13]; also results from Hubble Space Telescope data). Japanese astronomers observed NGC 7469 with the MAGNUM telescope between 2001 and 2003 [14].

2. OBSERVATIONS AND PRELIMINARY DATA REDUCTION

Our multicolor observations of the Seyfert galaxy NGC 7469 with the 1.5-m telescope of the Mt. Maidanak observatory were performed between 1997 and 2006, during two to three months each year. Starting in 1997, we observed with a TI 800×800 CCD camera, replaced since 2000 with an SIT 2000×800 CCD camera. On all occasions, we used Bessell $UBVRI$ filters. Both CCDs were cooled with liquid nitrogen. Observations obtained by O.V. Ezhkova et al. with the 48-cm AZT-14 and 60-cm Zeiss-600 telescopes between 1990 and 2001 as part of the ROTOR program were added for our variability analysis.

Observations between 1990 and 2001. A 28.9″ diaphragm used with the 60-cm telescope and a 14″–26″ diaphragm with the 48-cm telescope. The comparison star was SAO 127930, with RA = $23^h03^m30.5^s$, Dec = +08°48′24″ (2000.0), $V = 8.749^m$, $U-B = -0.016^m$, $B-V = 0.496^m$, $V-R = 0.292^m$. The techniques used to reduce the observations are described by Berdnikov [15]. The uncertainties of these observations are $\Delta V = B-V = 0.015^m$, $\Delta(U-B) = 0.04^m$, $\Delta(V-R) = 0.02^m$.

Observations between 1997 and 2006. These CCD observations enabled us to analyze data using different apertures: 10″, 15″, 20″, and 30″. Starting in 2000, the comparison star was star No. 1 in the list of comparison stars from [16], with RA = $23^h03^m31.3^s$, Dec = +08°52′00.3″ (2000.0), $B = 13.299^m \pm 0.011^m$, $V = 12.671^m \pm 0.006^m$, $R = 12.284^m \pm 0.014^m$, $I = 11.945^m \pm 0.014^m$; this star's brightness is comparable to that of the galaxy, and the star is within the same frame. The comparison star used in 1997–1998 SAO 127930 has the coordinates RA = $23^h03^m30.5^s$, Dec = +08°48′24″ (2000.0); its magnitudes I were determined via comparison to star No. 1 when they were observed in the same frame. We checked the star for variability.

In total, more than 2000 frames were processed. The reduction techniques were developed by the staff of the Mt. Maidanak Observatory, based on the MIDAS (Munich Image Data Analysis System) software package; these were improved with time, so that many of the reduction routines became partially or fully automatic, making it possible to obtain final results of long-term monitoring more rapidly. The second part of the reduction was done with the MATLAB and IDL software systems. Since we were not interested in attempting to detect vrey fast variations (on time scales of hours, i.e., shorter than one day), we averaged the data from each night (2–10 frames per night). The observational uncertainties increased only on nights near the full Moon or nights with poorer weather conditions. The uncertainties are between 0.001^m and 0.01^m for B, V, R, and I and 0.02^m for U. Since the comparison stars are in the same frame as the galaxy and at a small angular distance from it, we did not take into account any effects of atmospheric extinction or air-mass variations. All our data were corrected for extinction in the interstellar medium of the Galaxy. We reduced all the observations to the standard Johnson–Cousins system.

3. OBSERVATIONAL RESULTS AND ANALYSIS

We used all our data to plot master $UBVRI$ light curves for the galactic nucleus with an aperture of 28.9″, the diaphragm size used for early photometric measurements. Figure 1 presents the $UBVRI$ observations obtained between 1990 and 2006.

An analysis of these light curves (Fig. 1) reveals the presence of two activity cycles: from 1994 till 2002 and from 2003 till 2007. Most Seyferts demonstrate long-term variability of their nuclei, on time scales of several years, and short-time-scale, outburst-like variations on time scales from days to tens of days, called the S (slow) and F (fast) components. In the case of NGC 7469, the time scale for the S component was ∼8–9 years in the first activity cycle and ∼4–5 years in the later activity cycle during our monitoring. The F component was observed at all phases of the activity cycles. The S component is plotted in Fig. 2 as solid curves for the four filters (left-hand panels). The maximum of 1997–1998 and minima in 1994 and in 2002–2003 are clearly visible in these diagrams. To identify the slow component, we used fits with 5th- and 7th-order polynomials. The right-hand panels of Fig. 2 present the residual flux differences after subtracting the slow component from the general light curve. The residual difference displays several F components in the nuclear variations.

As an example, Fig. 3 displays the typical behavior of the F component of the $UBVRI$ variations (without the slow component subtracted) in 2003. Although the character of the variations is similar in all the optical filters, different time intervals exhibit variations with different amplitudes, as is demonstrated by our statistical analysis carried out using the technique described by Peterson [17].

Figure 4 shows the relationship between the flux ratio logarithm $\Delta \log F = \log(F(t_j)/F(t_i))$, where $F(t_i)$ is the flux from the galactic nucleus in a given filter at time t_i, and the time interval between the observations, $\Delta t = t_j - t_i$. The amplitude of the variability on time scales of days is lower than the corresponding amplitude for time scales of several months or years.

Comparing the light curves of NGC 7469 in the different filters, we find an increase in the flux from the nucleus with increasing wavelength (left-hand panels of Fig. 2). In the first activity cycle, the U-brightness difference between the maximum and minimum is 6.5 in relative intensity units, derived from the light curve in magnitudes (Fig. 1); this difference is 2.3 for B and

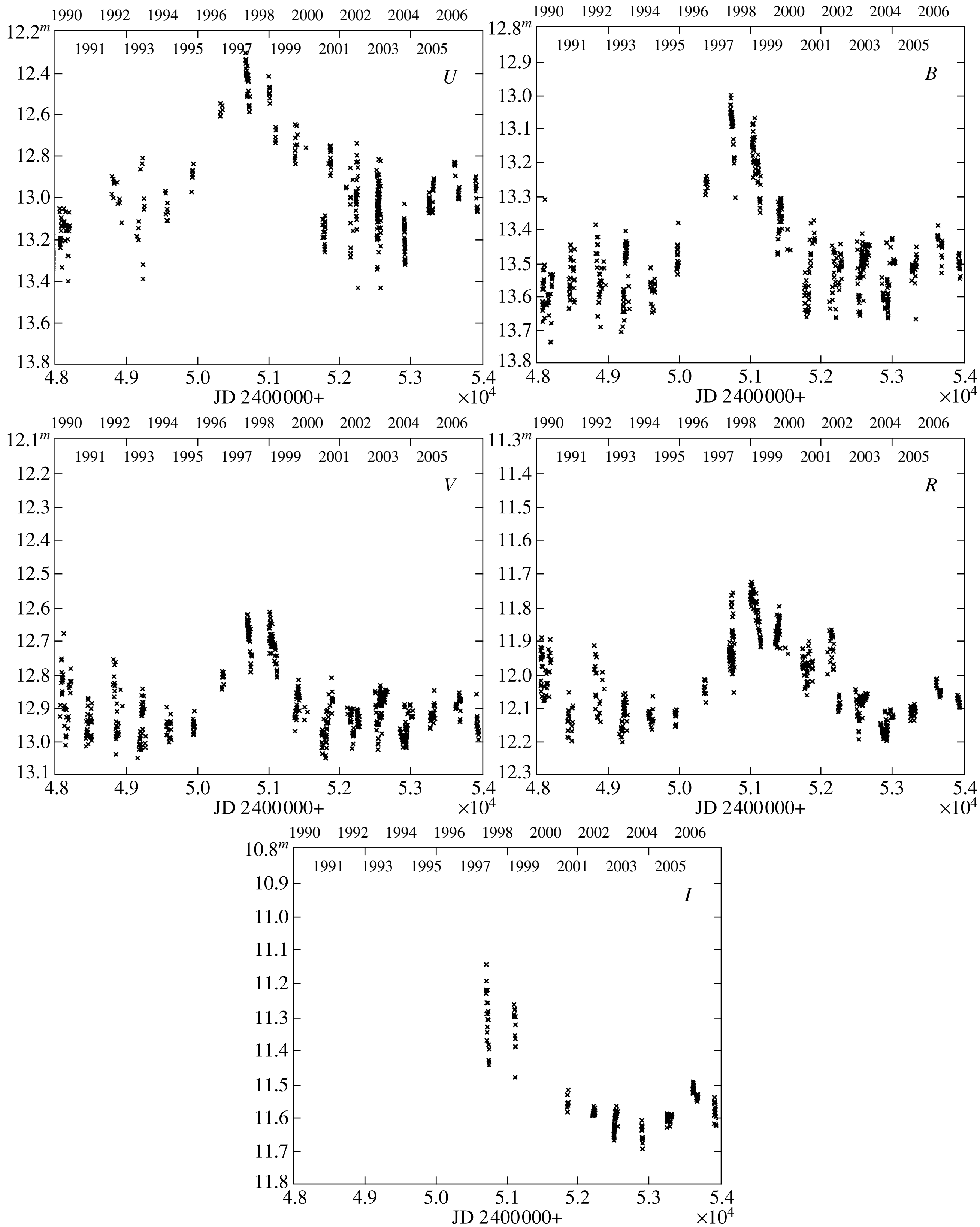

Fig. 1. *UBVRI* light curves of NGC 7469 for 1990–2006.

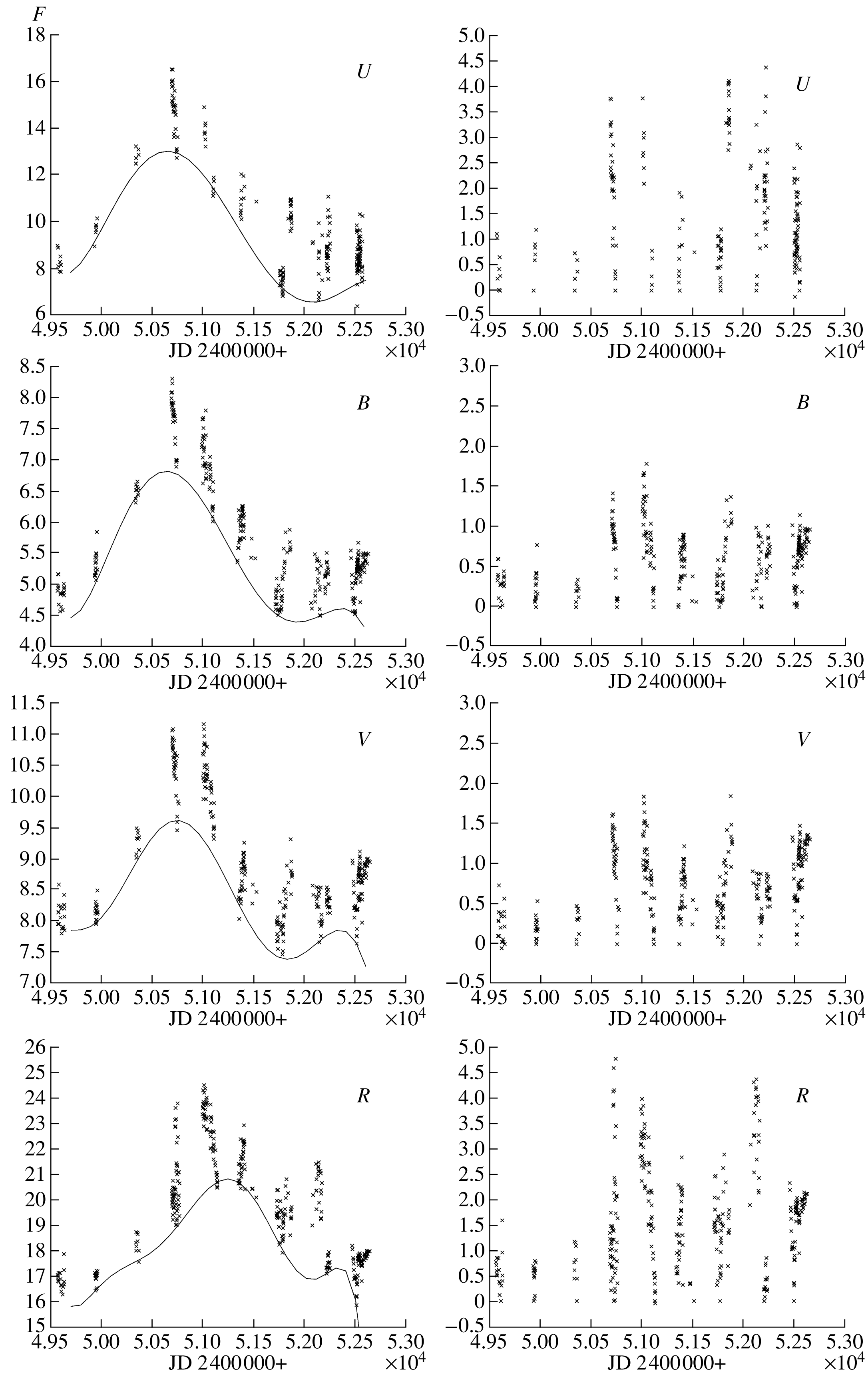

Fig. 2. Long-term (left) and short-time-scale (right) brightness variations of NGC 7469 in the *UBVR* filters for 1994–2002.

1.8 in V, i.e., almost the same as in B. However, this difference increased again to 4.0 in R.

Figure 2 (right-hand panels) demonstrates the same effect for the F component: we observe very strong variations in the U F component, lower outburst amplitudes in B and V, and higher amplitudes in R and I. Similar behavior was reported for the Seyfert NGC 4151 in [18]. The outburst duration for the F-component variability is the same in all the filters. The S component also has the same duration in all the filters.

In U, B, and V, we observed a rapid brightness increase of the S component from 1994 to 1997 and a slower fading from 1997 to 2002. The maximum of the first activity cycle occurred between 1997 and 1998. It will become possible to derive the true maximum more precisely after a comparison of all available observations.

The amplitude of the F component is always lower than that of the S component. For example, the difference of the B amplitudes for the S component is 0.5^m, while it is from 0.02^m to 0.4^m for the F component (in a $28.9''$ diaphragm).

Comparing our observations to those from earlier epochs [4], we find an increase in the time scale of the S component, from 3 years (1970s) to 8–9 years (1994–2002). After the minimum of 2002–2003, a new outburst was observed until 2007, with a maximum in 2005. This is also an S component, although it is weaker, with a duration of only 4 years.

4. COLOR CHARACTERISTICS

Multicolor photometry can be used to study the character of variations of the object's spectral energy distribution. We compared the color characteristics of the light curve of the central part of NGC 7469 to those for blackbody radiation from a gas, modeling the radiation from the accretion disk, in the $(U-B)-(B-V)$ two-color diagram (Fig. 5). The colors plotted in Fig. 5 were measured with a $28.9''$ aperture. The UV excess grows strongly with increasing luminosity of the variable source in the nucleus. It follows from Fig. 5 that the UV excess of NGC 7469 increases at the maximum of both cycles. The brightness at maximum was much higher in the first than in the second activity cycle. The UV excess increases with the brightness. The brightness increase and decrease correspond to color indices intermediate between those at the maximum and minimum. The variations of the color indices with brightness in Fig. 5 run parallel to the color-index variations for a blackbody with an increasing temperature. A rough estimate gives temperatures of about 10 000 K and 7000 K for the maxima in the first and second cycles, if most of the radiation of the variable source is

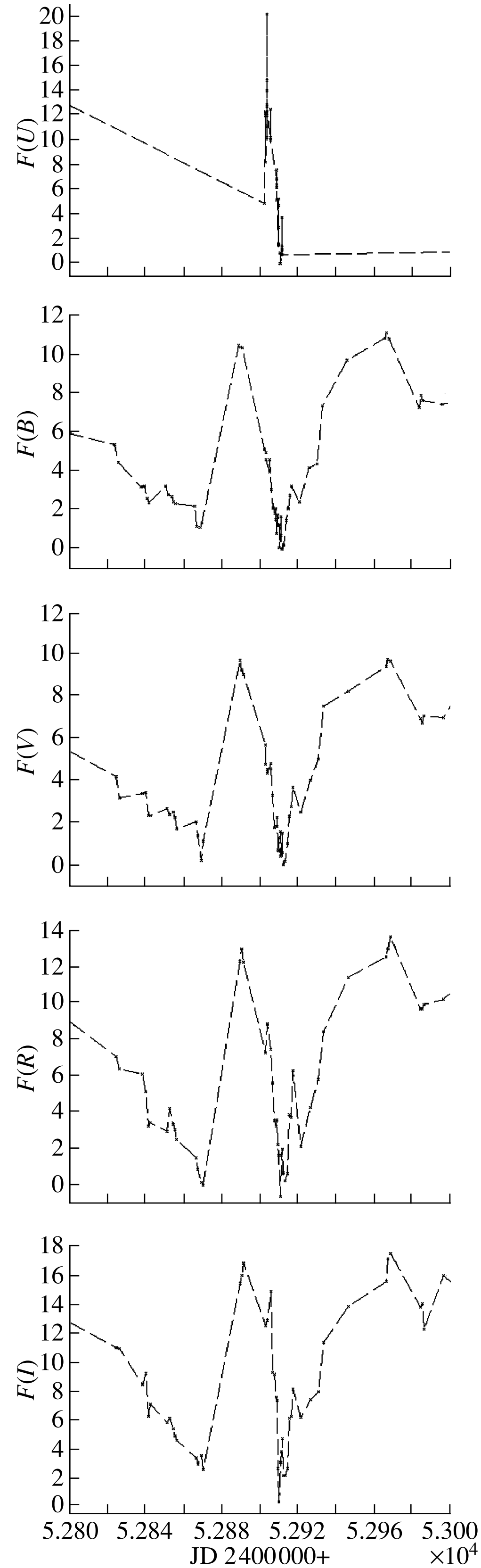

Fig. 3. Short-time-scale variability of the nucleus of NGC 7469 in 2003.

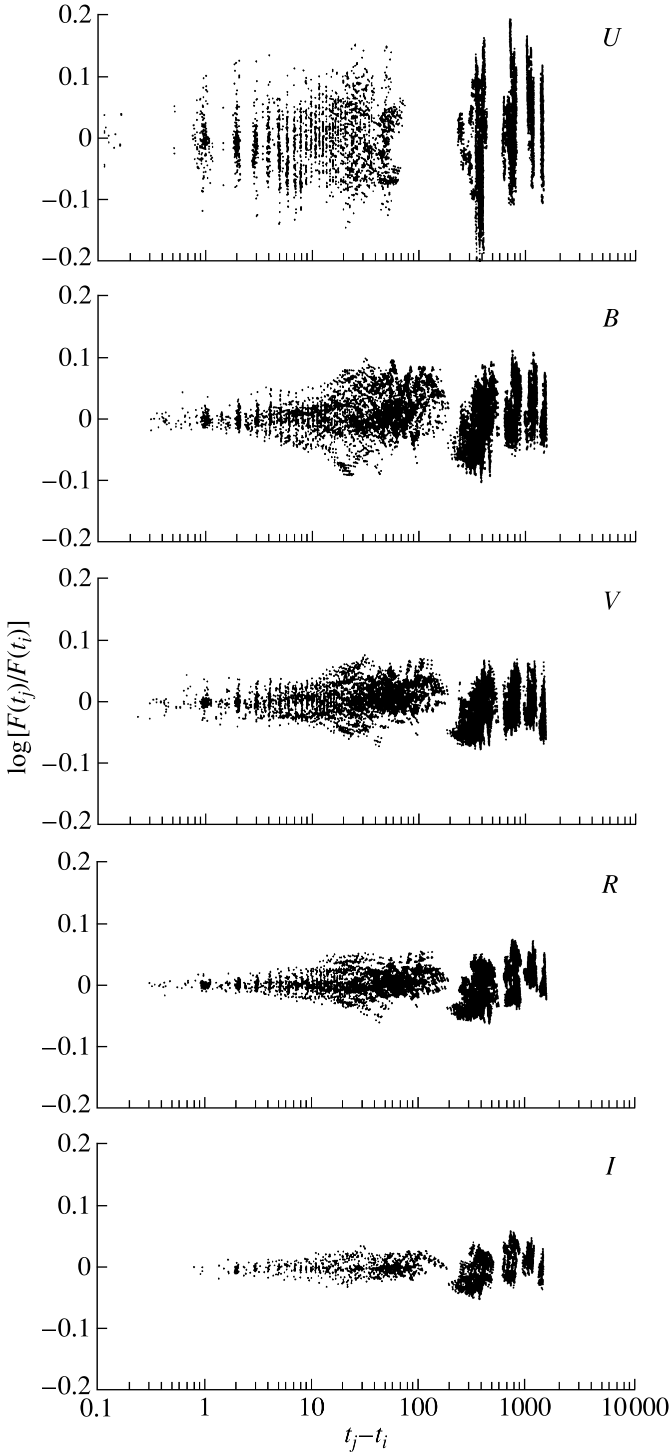

Fig. 4. Variability parameters of NGC 7469: dependence of $\Delta \log F = \log(F(t_j)/F(t_i))$ on $\Delta t = t_j - t_i$.

determined by blackbody radiation from the accretion disk. More accurate estimation requires taking into account the contribution from the galaxy and various emission regions; we are planning such an analysis in a future study. Note that variations of the color indices corresponding to an increasing UV excess during brightness increases are a characteristic feature of Seyferts (for example, see [19]).

CCD observations make it possible to measure the galaxy's brightness in different apertures, enabling estimation of the color-index variations at different distances from the nucleus. Figure 6 shows the de-

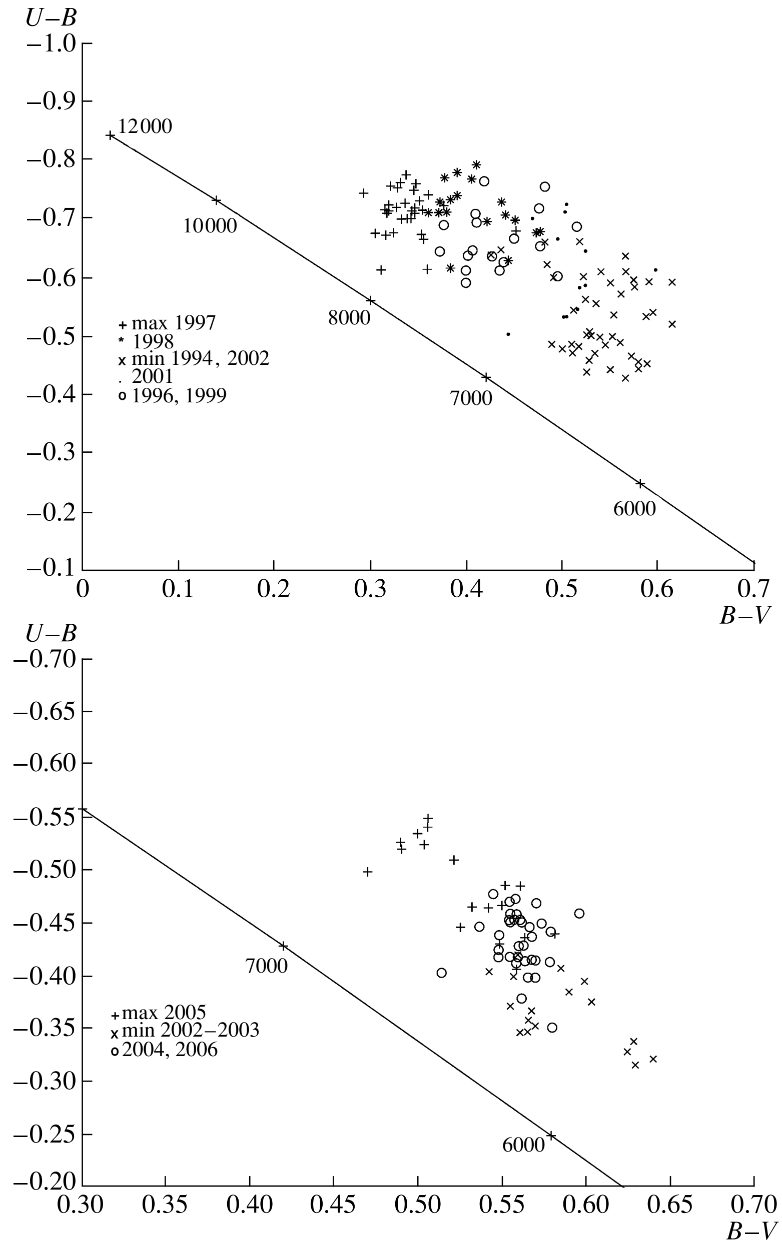

Fig. 5. Color indices of NGC 7469 in the $(U-B)-(B-V)$ two-color diagram for various activity periods in the first cycle, from 1994 to 2002 (top panel), and in the second cycle, from 2002 to 2006 (bottom panel).

pendence of the color index on the diaphragm radius. We find bluer colors with approach toward the nucleus; the contribution from the galaxy's central part is probably appreciable in large apertures. This effect was noted in [20].

5. CONCLUSIONS

It is generally accepted that the variability of Seyfert nuclei is associated with disk accretion onto a super-massive compact object, so that all features of the detected variations are due to the accretion disk [21, 22]. The increasing time scale of the slow component, which is related to the accretion disk, confirms the possibility of varying accretion conditions [23].

We have presented the results of $UBVRI$ observations of the nucleus of the Seyfert galaxy NGC 7469 obtained at the Mt. Maidanak Observatory in 1990–2006. We have plotted light curves for all these filters reduced to an aperture size of 28.9″. Our analysis of these light curves reveals the presence of fast variations, on time scales from several days to several tens of days, and slow variations, with a time

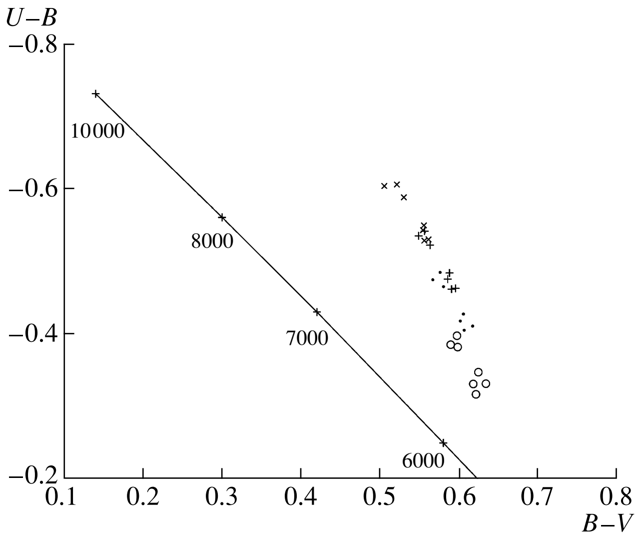

Fig. 6. Variation of the color indices of NGC 7469 in the $(U-B)-(B-V)$ two-color diagram with distance from its nucleus. The crosses correspond to an aperture of $r = 5''$, the pluses to $r = 7.5''$, the points to $r = 10''$, and the circles to $r = 15''$.

scale of ~8–9 years for the first activity cycle and 4–5 years for the second activity cycle of the nuclear variations.

Our observations have demonstrated the following.

(1) The character of the variations is the same for all the optical filters.

(2) The relative amplitudes of the variations of both components decreased with increasing wavelength from U to V, then increased again in R and I. In both activity cycles, the variation amplitude was especially large in U.

(3). The S component of the first activity cycle of NGC 7469 demonstrated a faster (three-year) brightness increase and a slower (five-year) brightness decline.

(4) The brightness maximum for the first activity cycle moves from 1997 in U, B, and V to 1998 in R. It probably occurred between 1997 and 1998.

Our analysis of variations of the color characteristics during the different activity periods revealed the following.

(1) We used $(U-B)-(B-V)$ two-color diagrams to compare the color characteristics of S outbursts and of blackbody radiation of a gas, modeling radiation from the accretion disk. The color of the galactic center became bluer at the maxima of both activity cycles.

(2) The color of the galaxy's central region becomes bluer with approach toward the center of the galaxy. One possible origin of this effect could be an appreciable contribution of light from the stellar population of the central region, especially in large diaphragms.

A deeper analysis will require the addition of data acquired with other telescopes. We are planning such a study, together with surface photometry of $UBVRI$ CCD frames of NGC 7469, which are needed to take into account the contribution from the stellar population of the central region of the galaxy.

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