# Rapid optical variations in the NGC 4151 nucleus

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On 13 nights in 1987–1988, the nucleus of the Seyfert galaxy NGC 4151 was monitored for $51^h$ in a search for rapid $V$-band variability. Several nights the brightness did vary by as much as $0^m.1$ within 15–30 min. The nucleus luminosity fluctuated at a maximum rate of $\sim 10^{37}$ erg/sec², or roughly 1% of the fastest rate permitted by the model of an accretion disk around a supermassive black hole.

## 1. INTRODUCTION

No sooner had Seyfert-galaxy nuclei and quasars proved to be optically variable, than surveys were initiated in hopes of detecting variability in these objects on short time scales. In 1967, for example, Fitch et al.,[1] having recorded variations in the nucleus of NGC 4151, remarked that the brightness might actually fluctuate during a single night, with a U-band amplitude as great as $0^m.15$.

The next year A. M. Cherepashchuk and one of us (V. M. L.) looked for evidence of rapid variability in the NGC 4151 nucleus. None was observed on one of those nights, but on another occasion[2] the ultraviolet brightness did appear to dim by $\Delta U \approx 0^m.15$ in ~30 min. In a more recent four-night survey, Lawrence et al.[3] encountered no fluctuations on three of the nights in excess of $\sim 0^m.05$, yet on one night the object again faded by $0^m.15$. Evidently, then, if Seyfert nuclei do undergo fast variability, it is not always present.

Much the same may be said of other types of active nuclei that have been observed at closely spaced times. Thus, Angione[4] found no nightly variability in the quasar 3C 273, whereas Lyutyi and Cherepashchuk[5] recorded two $\Delta B \approx 0^m.1$ flares on one of four nights. Similar results, with some authors reporting rapid variability for a given object and others not, have been obtained for BL Lacertae sources, including[6,7] OJ 287 and BL Lac itself.[8,9] (In each case the first paper cited mentions no rapid variability, while the second does.)

This ambiguity can hardly testing to observations of low quality. More likely the state of the object is responsible: fast variations may or may not be perceptible, depending on certain intrinsic properties. To resolve the issue, a special program of systematic observations is clearly needed.

The question of whether active nuclei experience rapid optical variability has lately become acute, now that high-speed fluctuations have been discovered in these objects at x-ray energies (see, for example, a current review by Urry[10]). Primarily on the basis of EXOSAT data, variability in the 2-10 keV range has been encountered in many active galactic nuclei on time scales from hundreds of seconds to a few hours. The amplitudes detected are anywhere from 10-20% to hundreds of percent, in several cases.

This letter describes our observations of the nucleus of the Seyfert galaxy NGC 4151 during 1987 and 1988 with a time resolution of about 9 min.

## 2. OBSERVATIONS

First of all, we point out that whenever nightly optical variability has been detected in active nuclei, its amplitude has been limited to 10% (or 20% for BL Lac objects). If a small telescope (50-60 cm aperture) is used, faint sources have to be observed in a single filter in order to provide ~1% accuracy for measurements taken 5-10 min apart. Although the variability amplitude of Seyfert nuclei is known to be greatest in the U band, we have chosen the V band, because atmospheric transmittance effects are much weaker in V than in U.

Our observations were carried out by the conventional technique used in differential measurements of variable stars except that two comparison stars were employed, the second serving as a control.[5] The following sequence was adopted: standard star — sky background — galaxy nucleus — control star — standard — background, and so on. We utilized four different telescopes: the two 60-cm instruments at the Shternberg Astronomical Institute's Southern Station, Nauchnyi, Crimea; the 48-cm at the Shternberg's high-altitude station at T'ian Shan near Alma-Ata, and the 60-cm telescope at the other Shternberg station on Mt. Maidanak in Soviet Central Asia.

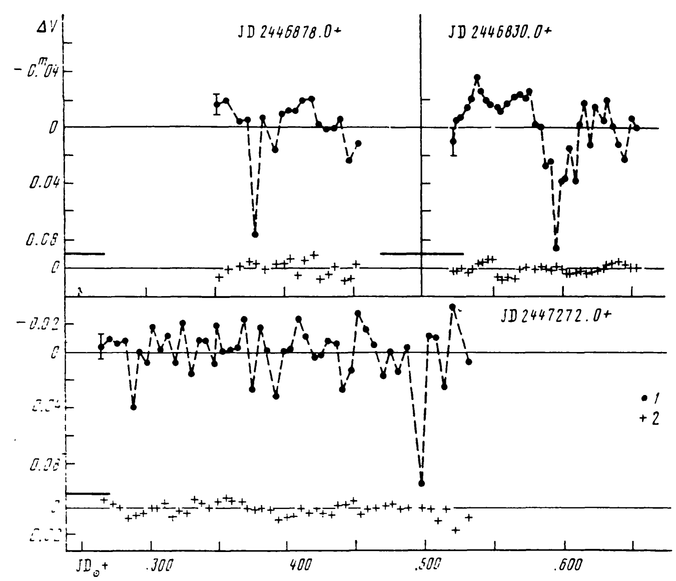


FIG. 1. V-band photometry of: 1) the NGC 4151 nucleus on the nights when it was most strongly variable (23/24 Mar 1987, 3/4 Feb 1987, 20/21 Apr 1988); 2) the control star 3C or, on JD 6830 only, the standard star C. The ordinate is the magnitude differential Δ V relative to the mean magnitude (Table I) for each night. The first point on each light curve is plotted with an error bar indicating the nightly mean error $\pm\sigma_{meas}$ of a single observation.

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TABLE I. High-Speed Photometry ( $\langle \Delta t \rangle$ = $0^d.006$) of NGC 4151 Nucleus

| Date | JD⊙ 244... | T | ⟨V⟩ | Standard deviation in V: GN | Standard deviation in V: C3 | N | θ" | Station |
|---|---|---|---|---|---|---|---|---|
| | | h m | m | m | | | | |
| 03/04.II.1987 | 6830.524—.655 | 3 09 | 11.862 | 0.025 | — | 36 | 3 | Crimea |
| 26/27.II | 6853.295—.496 | 4 49 | 11.824 | 0.011 | — | 36 | 4 | Alma-Ata |
| 23/24.III | 6878.354—.456 | 2 27 | 11.867 | 0.022 | $0^m.004$ | 18 | 5 | Alma-Ata |
| 29/30.IV | 6915.331—.441 | 2 38 | 11.919 | 0.011 | 0.005* | 33 | 7 | Crimea |
| 15/16.II.1988 | 7207.375—.628 | 6 04 | 11.803 | 0.007 | 0.008 | 55(63) | 4 | " |
| 16/17.II | 7208.382—.578 | 4 42 | 11.793 | 0.007 | 0.007 | 51 | 5 | " |
| 17/18.II | 7209.471—.625 | 3 42 | 11.781 | 0.005 | 0.006 | 30 | 2 | " |
| 09/10.IV | 7261.307—.436 | 3 06 | 11.867 | 0.012 | 0.006 | 22 | 3 | " |
| 12/13.IV | 7264.294—.442 | 3 33 | 11.854 | 0.013 | 0.003 | 26 | 4 | " |
| 13/14.IV | 7265.286—.481 | 4 41 | 11.865 | 0.011 | 0.005 | 27 | 4 | " |
| 19/20.IV | 7271.252—.385 | 3 12 | 11.860 | 0.006 | 0.006 | 28(10) | 3 | Alma-Ata |
| 20/21.IV | 7272.267—.534 | 6 24 | 11.886 | 0.021 | 0.005 | 47 | 4 | Crimea |
| 18/19.V | 7300.218—.326 | 2 36 | 11.854 | 0.010 | — | 24 | 2 | Maidanak |

Notes. — Asterisk, star F rather than C3 was the control; parenthesized quantities, number of measurements of C3 if different from number for GN.

TABLE II. V-Band Photometry of NGC 4151 Nucleus

| JD⊙ 244... | V | JD⊙ 244... | V | JD⊙ 244... | V |
|---|---|---|---|---|---|
| | m | | m | | m |
| 6830.524 | 11.880 | 6878.354 | 11.851 | 7272.350 | 11.893 |
| .526 | 11.865 | .361 | 11.848 | .356 | 11.884 |
| .529 | 11.863 | .370 | 11.863 | .361 | 11.883 |
| .534 | 11.854 | .376 | 11.862 | .367 | 11.882 |
| .537 | 11.850 | .381 | 11.942 | .372 | 11.861 |
| .541 | 11.835 | .387 | 11.860 | .377 | 11.912 |
| .544 | 11.845 | .396 | 11.884 | .383 | 11.867 |
| .548 | 11.852 | .401 | 11.858 | .388 | 11.884 |
| .551 | 11.855 | .406 | 11.855 | .394 | 11.916 |
| .555 | 11.856 | .411 | 11.856 | .400 | 11.884 |
| .557 | 11.859 | .416 | 11.848 | .405 | 11.884 |
| .562 | 11.853 | .423 | 11.847 | .411 | 11.861 |
| .567 | 11.848 | .427 | 11.866 | .416 | 11.874 |
| .571 | 11.847 | .433 | 11.869 | .422 | 11.889 |
| .576 | 11.850 | .438 | 11.868 | .427 | 11.887 |
| .578 | 11.844 | .443 | 11.861 | .432 | 11.877 |
| .582 | 11.869 | .449 | 11.891 | .438 | 11.879 |
| .586 | 11.870 | .456 | 11.879 | .443 | 11.911 |
| .589 | 11.898 | 7272.267 | 11.882 | .449 | 11.898 |
| .593 | 11.894 | .273 | 11.876 | .454 | 11.858 |
| .596 | 11.957 | .279 | 11.879 | .460 | 11.869 |
| .601 | 11.909 | .285 | 11.877 | .465 | 11.880 |
| .604 | 11.907 | .290 | 11.925 | .472 | 11.902 |
| .607 | 11.886 | .295 | 11.885 | .477 | 11.884 |
| .611 | 11.909 | .301 | 11.893 | .483 | 11.899 |
| .614 | 11.869 | .306 | 11.867 | .489 | 11.882 |
| .618 | 11.853 | .311 | 11.884 | .499 | 11.979 |
| .622 | 11.883 | .317 | 11.873 | .505 | 11.874 |
| .625 | 11.856 | .322 | 11.893 | .510 | 11.875 |
| .631 | 11.866 | .327 | 11.865 | .516 | 11.910 |
| .633 | 11.851 | .333 | 11.901 | .522 | 11.853 |
| .637 | 11.870 | .339 | 11.876 | .534 | 11.892 |
| .642 | 11.883 | .344 | 11.877 | | |
| .646 | 11.893 | | | | |
| .651 | 11.864 | | | | |
| .655 | 11.872 | | | | |

Measurements were made on 13 nights in 1987-1988; NGC 4151 was monitored for a total of $51^h$, and the average temporal resolution $\langle \Delta t \rangle = 0^d.006 \approx$ 9 min. The basic photometric data are assembled in Table I, which gives the date of each set of observations, the heliocentric JD at the beginning and end of the series, its duration T, the mean V magnitude in a 27" diaphragm, the standard deviation in the V data for the galaxy nucleus (GN) and the control star (C3), the number N of measurements taken, the diameter θ of a stellar seeing disk in arc seconds as estimated visually each night, and the observing station.

From the brightness distribution[11] in NGC 4151 we have estimated the error introduced by guiding inaccuracy: less than about 1% of the light is lost when the galaxy nucleus wanders by as much as half the diaphragm radius. An experimental guiding test gives the same reuslt.

The photon statistics (corrected for the sky background) indicate a photometric error of $0^m.005$-$0^m.011$ for the nucleus and $0^m.006$-$0^m.008$ for the control star (usually star C3, but star F served as the control on 29/30 April 1987). All measurements were made relative to the standard star C. The three comparison stars, C and the controls C3 and F, correspond to stars Nos. 1, 2, 5 of Penston et al.,[12] but we have adopted for star C the magnitudes and color indices ($V = 9^m.818$, $B-V = +0^m.596$, $U-B = -0^m.019$) given by Fitch et al.[1] Our values for the magnitude and colors of C3 ($V = 11^m.441$, $B-V = +1^m.053$, $U-B = +0^m.766$; error $\pm 0^m.005$) differ slightly from those determined by Penston et al.[12] ($11^m.47$, $+1^m.00$, $+0^m.80$, respectively;

TABLE III. Parameters of ΔV Data for Control Star and NGC 4151 Nucleus

| Data sample | $\bar{\sigma}_{meas}$ | Standard deviation (SD) | N | $SD/\bar{\sigma}_{meas}$ |
|---|---|---|---|---|
| C3 | 0.0066 ±3 | 0.0060 | 327 | 0.9 |
| $GN_{tot}$ | 0.0069 ±5 | 0.0134 | 433 | 1.9 |
| $GN_{const}$ | — | 0.0082 | 257 | 1.2 |
| $GN_{var}$ | — | 0.0185 | 176 | 2.7 |

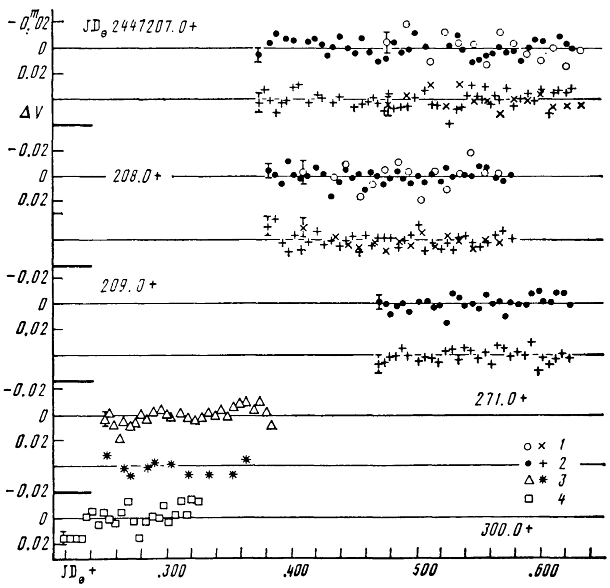


FIG. 2. Observations of NGC 4151 on several nights when it was not variable (15/16, 16/17, 17/18 Feb, 19/20 Apr, 18/19 May 1988). Ordinate ΔV as in Fig. 1. Different symbols designate measurements of (first symbol of each pair) NGC 4151 or (second symbol) the control star C3 with differing instruments: 1) the Shternberg Crimean Zeiss I; 2) the Crimean Zeiss II; 3) the Alma-Ata telescope; 4) the Mt. Maidanak telescope. Error bars on first point of both light curves.

for star C they obtained $9^m.85$, $+0^m.58$, $0^m.00$), but agree to within the errors. For star F we accept the Penston values [12] $V = 11^m.22$, $B-V = +1^m.02$, $U-B = +0^m.83$.

Certain conclusions can be drawn directly from Table I: the standard deviation for the control star is always close to the measurement error, whereas on three nights (3/4 Feb 1987, 23/24 Mar 1987, 20/21 Apr 1988) the standard deviation (the rms deviation of a single measurement) for the galaxy nucleus was about three times the measurement error, implying that the nucleus is definitely variable.

## 3. ANALYSIS OF VARIABILITY

Figures 1-4 summarize the results of our observations of the NGC 4151 nucleus and the control star C3. We have singled out three characteristic groups of observations: a) those definitely exhibiting substantial variability on a given night (Fig. 1 and, explicitly, Table II); b) those showing no trace of rapid variability (Fig. 2); c) those in which fast variability is suspected to a greater (Fig. 3a) or leasser (Fig. 3b) extent.

On 26/27 Feb 1987 the nucleus dimmed gradually by $0^m.02$ in a $6^h$ interval (dashed least-squares regression line in Fig. 3b); if this effect is eliminated, the standard deviation decreases from $0^m.011$ (Table I) to $0^m.009$, close to the measurement error. A comparatively slow ($2^h$-$3^h$) wave may still remain, of $\sim 0^m.005$ amplitude. The deviation of only one point on 29/30 Apr 1987 (middle part of Fig. 3b) exceeds $3\,\sigma_{meas}$, but this night had the poorest seeing of all (turbulence disk ~7"; see Table I). Quite likely both these nights belong in the second group — no variability on short time scales (tens of minutes).

Returning to Fig. 1, we see that on these three nights the NGC 4151 nucleus was unquestionably variable over intervals of 15-30 min. The fluctuations reach $0^m.1$ amplitude. To within the errors, the control star remain constant on 23/24 Mar 1987 and 20/21 Apr 1988. It was not photometered the night of 3/4 Feb 1987, so we have plotted the deviations of the standard star C from its mean magnitude as a check on the atmospheric transmittance. A correction has been applied for the trend due to the change in air mass. Clearly the atmosphere remained steady on this night and the variability of the galaxy nucleus relative to the standard star is surely intrinsic to the nucleus.

All the data were subdivided into three samples for further analysis: measurements of the control star C3, of the nucleus at constant brightness ($GN_{const}$: 26/27 Feb, 29/30 Apr 1987; 15/16, 16/17, 17/18 Feb 1988; 19/20 Apr, 18/19 May 1988), and of the varying nucleus ($GN_{var}$: 3/4 Feb, 23/24 Mar 1987; 9/10, 12/13, 13/14, 20/21 Apr 1988). The parameters describing these samples and all the nucleus observations combined ($GN_{tot}$) are given in Table III.

Figure 4 displays histograms for the ΔV values in the $GN_{const}$, C3, and $GN_{var}$ samples, along with corresponding Gaussian curves whose standard deviation is $\bar{\sigma}_{meas}$. The control-star measurements (Fig. 4b) fit the normal curve perfectly but their standard deviation is somewhat smaller than $\bar{\sigma}_{meas}$, presumably because the measurement error had been overestimated. The $GN_{const}$ data set also has very nearly a normal distribution. By contrast, the histogram for $GN_{var}$ does not at all resemble the Gaussian curve. Variability of the NGC 4151 nucleus is the only possible explanation.

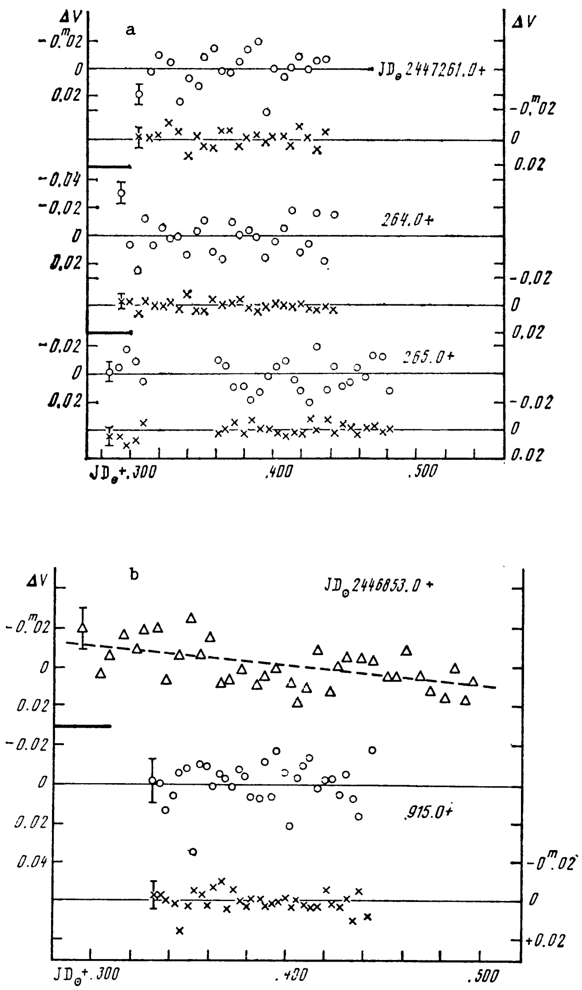


FIG. 3. Circles and triangles, observations of NGC 4151 (a) strongly or (b) weakly suspected of exhibiting low-amplitude variability; crosses, measurements of the control star C3.

## 4. DISCUSSION

The salient conclusions to be drawn from our ~9 min resolution photometry are:

1. A $51^h$ patrol, conducted on 13 nights spanning 16 months, has definitely disclosed rapid (time scale 15-30 min) variability in the V-band radiation of the nucleus of the Seyfert galaxy NGC 4151 on 3 of the 13 nights. These nights represent about $12^h$ of patrol or 25% of the total observing time.

2. On five nights, there definitely was no rapid variability with an amplitude above 3 $\sigma_{meas}$ (about $10^h$ of patrol time, or 35%).

3. Whether or not fast variations occur apparently has nothing to do with the mean nightly brightness level. During our program the average magnitude fluctuated from $11^m.78$ to $11^m.92$, and on the nights at either extreme there was no appreciable variability.

Interestingly, Massaro et al.[13] have reached identical conclusions from their H-band photometry of the BL Lac object OJ 287 in 1986: on some nights the object was variable by ~20% in 20-30 min, while on others no variability could be detected, to within the errors. The occurrence of fast variations again did not depend on the average brightness each night. The temporal resolution of the OJ 287 measurements, about 8 min, was about the same as ours. Rapid light fluctuations were observed on three of four nights.

In view of these findings it now becomes understandable that isolated, non-systematic observations have led to conflicting results: variability is not always present. Systematic programs are therefore essential in searching for short-term fluctuations in active galactic nuclei.

Although we have not analyzed our data for periodicities, an attempt has been made to determine the minimum characteristic variability time. To this end we have singled out those upward or downward brightness differentials of amplitude greater than $0^m.04$ (about 5 standad deviations (SD) for the sample $GN_{const}$ (see Table III)) or $0^m.05$ (~6 SD). On this basis we find a minimum variability time scale of 11-15 min and an amplitude of ~$0^m.07$ (about 7%). The same time scale applies to both dimmings and brightenings, although as Fig. 1 demonstrates, the sharpest fluctuations take the form of abrupt drops in luminosity.

Throughout our observing program the NGC 4151 nucleus persisted in its low activity state, which commenced [14,15] in 1984. The minimum visual intensities recorded for NGC 4151 in the 27" diaphragm over the past 20 yr are $V_{min} = 12^m.03 \pm 0^m.10$ in 1968, $11^m.96 \pm 0^m.02$ in 1984, $11^m.93 \pm 0^m.03$ in 1985, and $11^m.95 \pm 0^m.02$ in 1987. These have an average value $V_{min} = 11^m.97 \pm 0^m.02$. The color indices at the current minimum, $B-V = +0^m.94 \pm 0^m.05$, $U-B = +0^m.06 \pm 0^m.10$ in the 27" aperture, are equal (within the errors) to the mean colors in a 27"–14" annulus ($+0^m.95 \pm 0^m.02$, $+0^m.09 \pm 0^m.04$) over 10 yr of observation.[16] Since the color indices even in a 13"–7" radius annulus are attributable to the galaxy's stellar component,[11] the value $V_{min} = 11^m.97$ presumably represents the radiation in the 27" diaphragm coming from the stars in NGC 4151; the variable source accounts for no more than a few percent.

During our monitoring of the rapid variability, the nucleus (on the average) has not faded below this $V_{min}$ value: on the nights of 3/4 Feb, 23/24 Mar, 29/30 Apr 1987, and 20/21 Apr 1988 the faintest measurements were $11^m.95$, $11^m.94$, $11^m.95$, $11^m.98$, respectively, so that the mean minimum was $\langle V_{min} \rangle = 11^m.96 \pm 0^m.01$. The three ~$0^m.1$ dips of this kind illustrated in Fig. 1 lasted 16-45 min. In July 1983 the object exhibited a similar weakening in the soft x-ray range [17] (0.04-2 keV), but of much greater amplitude, a factor of ~3 (duration ~30 min). It was conjecture[17] that the x-ray source might have been occulted by a star located within 1 pc of it.

In terms of the model of disk-type accretion by a supermassive black hole, it would seem more plausible that the disk luminosity should vary both at x-ray energies and optically (occultations by a star twice within a month and a half are unlikely). Accepting that when $V = V_{min} = 11^m.97$ the luminosity of NGC 4151 in the 27" zone derived basically from the stellar component ($L_V{}^* = 2.5 \cdot 10^{42}$ erg/sec), and taking the luminosity at maximum light ($V = 11^m.40$, in 1971) to be $L_V{}^{max} = 4.3 \cdot 10^{42}$ erg/sec, we may infer that the maximum luminosity of the variable source (an accretion disk?) is $L_V{}^{var} = 1.8 \cdot 10^{42}$

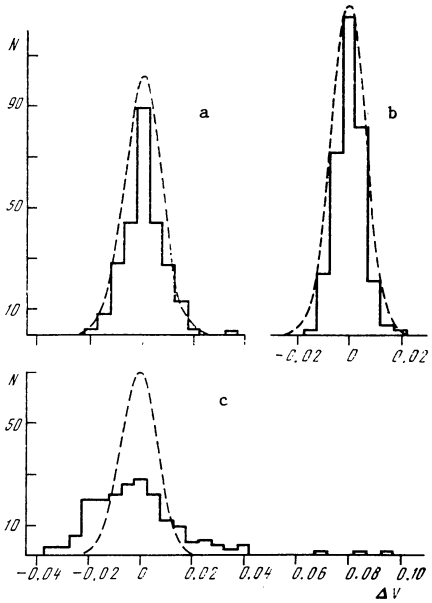


FIG. 4. Histograms indicating how the magnitude differentials $\Delta V$ are distributed for three samples of data: a) $GN_{const}$; b) the control star; c) $GN_{var}$. Dashed curves represent normal distributions for these samples, each with the corresponding dispersion $\bar{\sigma}_{meas}$; N is the number of points in each bin.

erg/sec. Then the mean level $V = 11^m.85$ during our observations would correspond to a disk luminosity of $\sim 2\cdot 10^{41}$ erg/sec, and the amplitude $\Delta V \approx 0^m.1$ of the rapid variability would be equivalent to a luminosity amplitude $\Delta L_V \approx 2\cdot 10^{40}$ erg/sec.

We may conclude, then, that the fast (~15 min) fluctuations we have recorded in the light of the NGC 4151 nucleus represent oscillations of $\sim 10^{40}$ erg/sec amplitude in the luminosity of the variable source, whose luminosity is changing at a rate of $\sim 10^{37}$ erg/sec$^2$. By comparison, the maximum possible rate of change in luminosity that might be observed [10] is $\Delta L/\Delta t \sim 3\cdot 10^{42}\delta$ erg/sec$^2$, where $\delta \gtrsim 1$. Thus the rate of change that we have detected is about 5 orders of magnitude below the fastest possible rate, $\Delta L_{Edd}/\Delta t$.

In active galactic nuclei the luminosity of the variable sources evidently is at most $10^{-3}$-$10^{-2}$ of the Eddington value [18,19] $L_{Edd}$. Accordingly NGC 4151 and other such objects might sometimes exhibit luminosity fluctuations at rates of $3\cdot 10^{39}$-$3\cdot 10^{40}$ erg/sec$^2$, or 2-3 orders of magnitude greater than the reate we have recorded. (In the x-ray range, rates as high as $3\cdot 10^{41}$ erg/sec$^2$ are observed.)

In March 1988 a strong infrared flare (in the J,H,K bands) was witnessed in the quasar 3C 273. Within a single day the J-band flux density jumped [20] from 46 to 66 mJy, or nearly 50%, corresponding to a rate of luminosity change of $\sim 4\cdot 10^{40}$ erg/sec$^2$. For the Seyfert galaxy NGC 7469, the rapid variability of the nucleus [21] (by 5-10% in ~15 min) is equivalent to $\Delta L/\Delta t \sim 10^{38}$ erg/sec$^2$, since NGC 7469 has an optical luminosity an order of magnitude higher than NGC 4151.

## 5. CONCLUSIONS

Our analysis of the rapid optical variability in the nucleus of the Seyfert galaxy NGC 4151 during a $51^h$ patrol on 13 nights in 1987-1988 has shown that:

1. Variability of up to 10% amplitude can occur within 15-20 min (by about $0^m.07$, on the average, in 11-15 min).

2. On some nights (~30% of the total patrol time), however, fast variations may be altogether absent.

3. Whether or not rapid variability is present evidently does not depend on the mean nightly brightness level, that is, the general state of activity in the nucleus.

4. The maximum rate of luminosity change that we have recorded for the variable source (accretion disk?) in NGC 4151, roughly $10^{37}$ erg/sec$^2$, is at most ~1% of the greatest possible rate.

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