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CONCURRENT RADIO, INFRARED, OPTICAL, AND X-RAY OBSERVATIONS OF THE NUCLEUS OF THE SEYFERT GALAXY NGC 4151

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ABSTRACT

The authors observed the nucleus of the Seyfert galaxy NGC 4151 during 1977 late May and early June at X-ray energies from 20 to 200 keV using the high-energy X-ray spectrometer on *OSO 8*, and at radio frequencies of 2695 and 8085 MHz using the NRAO[2] interferometer at Greenbank, West Virginia. Concurrently with these observations, data were taken in the visual, and at infrared wavelengths of 1 to 12 μm. Observations are also available from 2 to 6 keV during this interval using the *OSO 8* proportional counter.

The optical data show variability by approximately a factor of 2 within the observing period. This is comparable to the variability in the 2 to 6 keV X-ray flux. However, no variability was measured at infrared or radio frequencies during the observing period.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: Seyfert — infrared: sources — radio sources: galaxies — X-rays: sources

I. INTRODUCTION

The Seyfert galaxy NGC 4151 is a highly inclined spiral 19 Mpc distant. Like Centaurus A it has been observed at frequencies from radio to γ-ray. Observations over the entire electromagnetic spectrum are necessary to understand the nature of the emission mechanism which produces the activity in the Seyfert nucleus.

At radio frequencies, NGC 4151 is a relatively weak and constant source, and has consequently not been extensively observed. De Bruyn and Willis (1974) measured the total flux of the nucleus to be 135 ± 10 mJy at 4.996 GHz (6 cm) using the Westerbork aperture synthesis telescope. Colla *et al.* (1975) have reported that the power-law spectral index, α, from 0.41 to 4.996 GHz (6 to 73 cm), has a value of 0.74 ± 0.05. On 1976 Oct 31 Condon and Dressel (1978) observed NGC 4151 using the NRAO three element interferometer and reported the flux to be 188 ± 10 mJy at 2.695 GHz and 89 ± 10 mJy at 8.085 GHz. The observations of Colla *et al.* and Condon and Dressel are in reasonable agreement.

At infrared frequencies, Seyfert galaxies in general, and NGC 4151 in particular, have been observed extensively. Considerable controversy exists over the nature and degree of the apparent variability. Penston *et al.* (1971, 1974) have detected variability in the infrared at 1.6 and 2.2 μm using a 15″ aperture, and at 3.4 μm using a 10″ aperture. Rieke and Low (1972) obtained values of 4.3 ± 0.7 Jy at 33.5 μm for observations taken on 1975 Feb 18–19 using an 8″.5 aperture, and 1.2 Jy at 10 μm. There was no evidence for variability at either frequency. More recently, O'Dell *et al.* (1978) have reported data that suggest that the infrared flux did not vary in time at wavelengths greater than 1.25 μm during their observing times, which extended from 1976 Mar 31 through 1980 Feb 4. Lawrence *et al.* (1980) also note no change in the *K*-band observations taken during the week of 1979 May 17–24. Kemp *et al.* (1977) measured a polarization of $0.13 \pm 0.06\%$ at 10 μm.

At optical frequencies, Penston *et al.* (1971, 1974) have observed variability in the *UBV* flux measurements from the nucleus of NGC 4151. The observations showing this variability were made with a 25″ aperture and were conducted concurrently with the infrared observations mentioned above. Lyuty and Pronik (1975), on the basis of a compilation of their own and previous results, state that the *U* magnitude of the nucleus of NGC 4151 varies by 1 mag over periods of several years, and also exhibits short flares of 0.5 to 0.8 mag on time scales of 20^d to 100^d. O'Dell *et al.* (1978) confirm that the source is variable in the *UBV* bands. However, Lawrence *et al.* (1980) report no significant variability in their *V*-band data, which were taken concurrently with the *K*-band

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measurements cited above. Ultraviolet observations by Wu and Weedman (1978) from the *ANS* satellite suggest variability at wavelengths shorter than that of the *U* band.

NGC 4151 is a relatively weak X-ray source at low energies. Gursky *et al.* (1971) report a 3.8 σ detection of a flux in the direction of NGC 4151 using the *Uhuru* satellite. The spectrum of NGC 4151 is, however, very hard. An X-ray flux from 7 to 110 keV has been detected by Baity *et al.* (1975) with a spectrum of $1.2 \times 10^{-2} E^{-1.1 \pm 0.2}$ photons $\mathrm{cm^{-2}\,s^{-1}\,keV^{-1}}$. Ives, Sanford, and Penston (1976) suggest, on the basis of a disagreement between their *Ariel* value and the *Uhuru* flux measured in 1970–71, that absorption of the low-energy X-rays may have changed. However, they find no evidence for variability of the power-law (6–30 keV) portion of the spectrum in their data, taken in 1974 Nov and 1976 Jan. Ulmer (1977) reports flux levels from *Uhuru* (2–6 keV) which vary from 4.8 to 12.7×10^{-11} ergs $\mathrm{cm^{-2}\,s^{-1}}$ on time scales of less than a week. Tananbaum *et al.* (1978) report variability on much shorter time scales (10 minutes or less) by a factor of 6 (+2, −2.2). Mushotzky, Holt, and Serlemitsos (1978) have shown that the flux from the nucleus at 2–6 keV varies by a factor of 2 on time scales of days. However, they do not find evidence of significant changes in the absorption coefficient or the power-law spectral index of 1.42 ± 0.06 used to fit their data. Using the *Ariel 5* data base, Lawrence (1980) has reported frequent 2–10 keV variability on time scales of days over a 4 yr period. Auriemma *et al.* (1978), Schoenfelder, Graser, and Dougherty (1977), and Perotti *et al.* (1979, and references cited therein) have reported the detection of X-rays and γ-rays at energies from ~40 keV to nearly 1 MeV. Bignami *et al.* (1979) have established important upper limits to the γ-ray flux at energies greater than 10 MeV. More recently, Coe *et al.* (1980) report detection of a hard X-ray spectrum which extends to 200–300 keV.

The observations reported here were made to establish an electromagnetic spectrum from radio to X-ray of the nucleus of NGC 4151 and to determine the presence or absence of concurrent variability between the various portions of that spectrum.

II. OBSERVATIONS

NGC 4151 was observed at radio, infrared, optical, and X-ray frequencies during the interval from 1977 May 18 through Jun 12. The radio observations at 2.695 and 8.085 GHz were taken by JHB using the NRAO three-element interferometer at Greenbank on 1977 May 31 and 1977 Jun 3. The data were reduced using the standard NRAO programs (Hjellming 1973) and are listed in Table 1 and plotted in Figure 1. An upper limit obtained by Ulich (1977) is also plotted in Figure 1.

Infrared measurements were taken by Rieke (1977) and Pipher (1977), and optical (*UBV* photometry) measurements of the source were taken by Wisniewski and Tapia (Tapia 1977). These data are plotted as an infrared to ultraviolet spectrum in Figure 2. The infrared measurement taken by Rieke (1977) used an 8″.5 aperture for measurements from 1.25 to 3.45 μm, and a 5″.9 aperture at wavelengths from 4.9 to 12.2 μm. The data from Pipher (1977) were taken with an 11″ aperture. However, Penston *et al.* (1971, 1974) do not show a strong angular dependence of the infrared flux for apertures ranging from 5″ to 10″ at a wavelength of 1.6 μm or greater. Because of this, we have not attempted to normalize the infrared observations to a constant aperture. The data are in general agreement with the data of O'Dell *et al.*. (1978) which were taken at varying apertures ranging from 9″ to 27″.

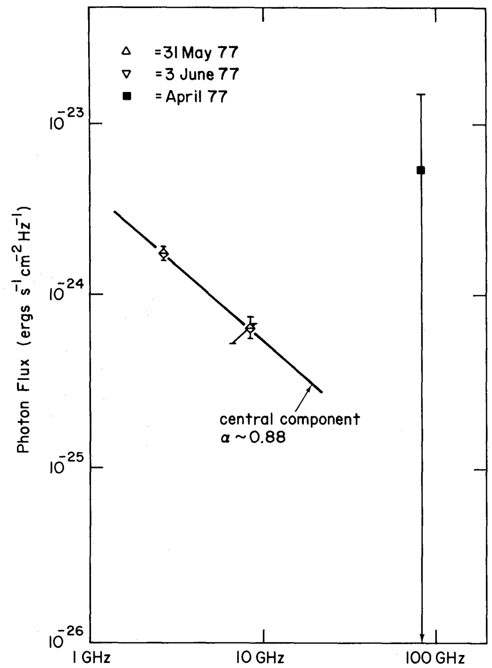

FIG. 1.—Radio observations of the nucleus of the Seyfert galaxy NGC 4151 taken with the NRAO three element interferometer at Greenbank, WV. The upper limit was obtained by Ulich (1977).

TABLE 1

RADIO FLUX DENSITY OF THE NUCLEUS OF NGC 4151

Date (1977)	S (mJy)	Standard Deviation (mJy)
	2.695 GHz	
31 May ...	169.3	12.3
3 Jun	171.8	8.0
	8.085 GHz	
31 May ...	62.8	11.7
3 Jun	60.7	6.4

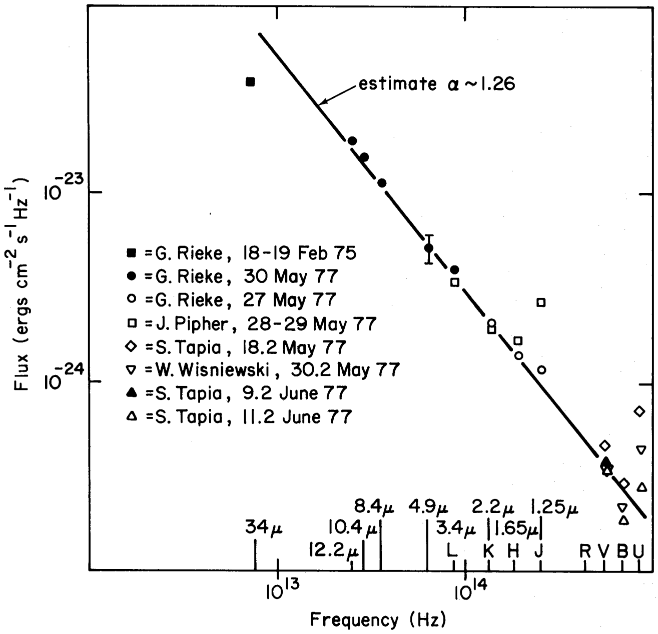

FIG. 2.—Infrared and optical observations of NGC 4151. The data are taken from the sources indicated in the text. The solid line is a power law fitted to the data. The 34 μm data point taken by Rieke and Low (1972) and the radio data at lower frequencies suggest a turnover in the infrared spectrum at $\sim 10^{12}$ Hz.

The optical (*UBV*) measurements taken on 1977 May 18.2, 1977 June 9.25 and 11.2 were all made using an aperture of 5″, while the data taken on 1977 May 30.2 were obtained with an aperture of 10″. Because the optical flux does exhibit an aperture dependence, the 1977 May 20.2 data point was normalized to a 5″ aperture using an extrapolation based on the aperture dependence obtained by Penston *et al.* (1971, 1974). The uncertainties associated with the infrared and optical points are typically ± 0.02 mag.

High-energy X-ray observations of the nucleus of NGC 4151 were taken using the high-energy X-ray spectrometer on board *OSO 8* (Dennis *et al.* 1977) and were reduced using a SKYMAP analysis routine as described in Beall (1979). The data are compared to an extrapolation of the data obtained by Mushotzky *et al.* (1978) in Figure 3. Radio, optical, and low-energy (2–6 keV) X-ray flux densities are shown as a function of time in Figure 4.

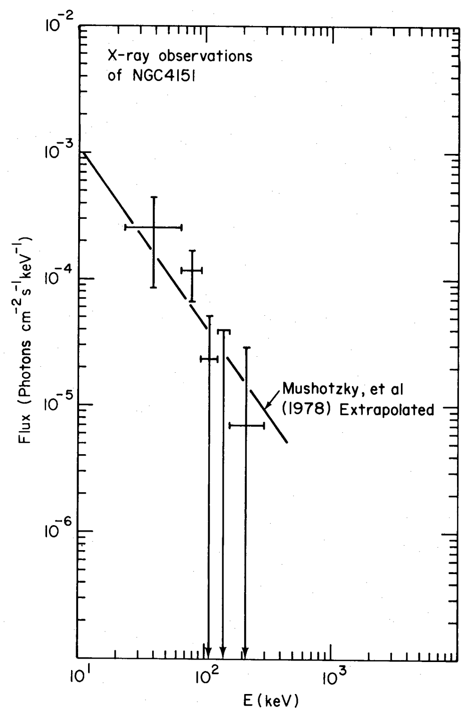

FIG. 3.—The X-ray spectrum of NGC 4151 was obtained using the SKYMAP technique (Beall 1979) on the high-energy X-ray data from the *OSO 8* high energy X-ray spectrometer. An extrapolation of the low-energy data (Mushotzky *et al.* 1978) is plotted for comparison.

III. DISCUSSION

The reported observations provide data on the spectrum and variability of the radiation from the nucleus of NGC 4151 over a wide range of frequencies during the observing period. No evidence is found for variability at radio frequencies. This is consonant with the unab-

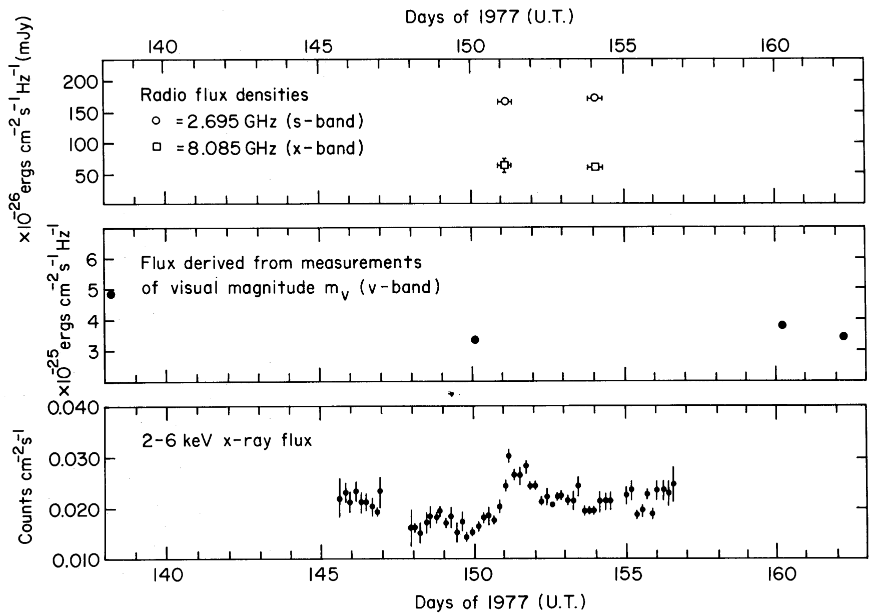

FIG. 4.—The variability of the nucleus of NGC 4151 at radio, optical, and low-energy X-ray frequencies during the observing period. Data are taken from Mushotzky *et al.* (1978), Tapia (1977), and the current work.

sorbed power-law spectra, which are commonly associated with an extended synchrotron source. Long-term variability cannot, however, be entirely ruled out.

There is also no evidence for variability in the infrared portion of the spectrum at wavelengths greater than 2.2 μm. There is apparent variability at 1.25 and 1.65 μm, but it is possible that the variability may result from instrumental differences between the two systems involved in the observations or from the different apertures used by Rieke and Pipher at 1.25 μm.

In contrast with the radio and infrared observations, the *UBV* photometry does show significant variability. This data is plotted in Figure 4 with the 2–6 keV X-ray data of Mushotzky *et al.* (1978), which also shows significant variability. The source is sufficiently weak that daily variability at energies above 20 keV cannot be detected with the *OSO 8* high-energy X-ray spectrometer.

The composite spectrum from radio to γ-ray is plotted in Figure 5 for NGC 4151. The radio spectrum is relatively weak compared to that of the nucleus of Centaurus A (NGC 5128) or the quasar, 3C273 (Beall 1979). A straight-line extrapolation of the radio spectrum falls below the observed X-ray spectrum. On the basis of this fact, and the lack of observed variability of the radio data, it is unlikely that synchrotron photons responsible for the radio observations are inverse Compton-scattered to produce the observed X-ray flux.

The infrared spectrum at wavelengths greater than 3.4 μm is reasonably well fit by a power law with a spectral index of 1.26. This infrared spectrum is not likely to be produced by synchrotron radiation. It may, however, be produced by the summed emission of a number of thermal sources (stars and dust) with varying temperatures (Rieke 1977). In the latter view, the thermal emission from the nucleus may be excited by the nonthermal source, ultraviolet light, or particle interactions. The apparent lack of variability of the infrared radiation at wavelengths greater than 2 μm suggests that the mechanism associated with the infrared flux is not directly related to the variable, nonthermal source represented by the X-ray data.

We note that the *UBV* photometric observations may be fitted by a power-law spectrum. Wu and Weedman (1978) find that the corrected spectrum for the ultraviolet continuum can be fitted by a power law with a spectral index of 1.13 ± 0.1. Boksenburg *et al.* (1978) report that the spectrum from optical to ultraviolet may be fitted by a power law with a spectral index of 1.0. They suggest, however, that the spectrum tends to flatten toward longer wavelengths.

Unlike the nucleus of Centaurus A (NGC 5128) (Beall *et al.* 1978 and Mushotzky *et al.* 1978), the radio and X-ray flux from the nucleus of NGC 4151 did not vary concurrently. This conclusion is based on the data in Figure 4 which show that the radio flux from the nucleus of NGC 4151 did not vary, while the 2–6 keV X-ray flux varied by a factor of $\sim$2 during the observing period. Lack of variability at radio frequencies is also consistent with the lack of evidence for synchrotron self-absorption, which in turn suggests that the radio source in the nucleus is extended. We are left with a

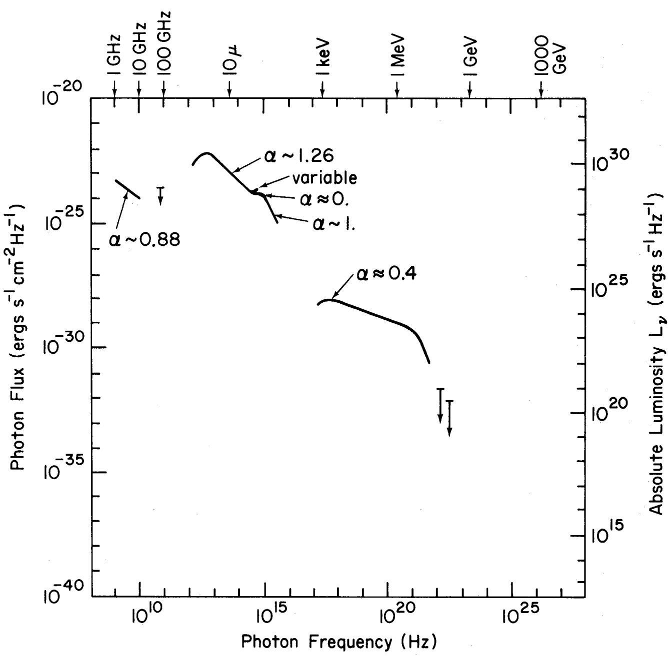

FIG. 5.—Concurrent radio, optical, and X-ray observations of the nucleus of NGC 4151. The data are shown as solid lines and are taken from the references cited in the text.

possible association between the variable optical and low-energy X-ray sources. Unfortunately, due to lack of coverage, we have evidence only that the optical and X-ray fluxes varied during the observing period. We do not know if they varied concurrently.

Information on possible concurrent variability at optical, ultraviolet, and X-ray frequencies must be obtained from future studies of this active galaxy. Such studies can further constrain models of a source environment which produces some of the most luminous objects in our universe.

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Note added in proof.—The recent paper by Lebofsky and Rieke (Nature, **284**, 410 [1980]) reports near-infrared flux measurements of NGC 4151 and four other Seyfert galaxies. Lebofsky and Rieke's data indicate long-term (~ 1 yr) variability of NGC 4151 at 2.2 μm, as well as variability on shorter time scales at shorter wavelengths.

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