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A BROAD-BAND CONTEMPORANEOUS STUDY OF THE SEYFERT GALAXY NGC 4151

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ABSTRACT

The authors observed the Seyfert galaxy NGC 4151 on 1980 May 18 at hard X-ray/low gamma-ray energies using the MISO telescope. No gamma-ray excess was found between 100 keV and 16 MeV and only a 3.5 σ excess was detected in the hard X-ray detector in the energy range 35–105 keV. Concurrently with this measurement, a program of ultraviolet and infrared observations was organized. Contemporaneous observations are also available in the optical and soft X-ray (2–10 keV) spectral regions. All these observations, along with monitoring studies performed over the period 1980 January–May, provide data on the spectrum and variability of the radiation from NGC 4151 over a wide range of frequencies prior to and during the MISO measurement. The data collected are used to estimate the properties of the radiation of this Seyfert galaxy and to constrain models of a central powerhouse which produces one of the most luminous objects in the sky.

Subject headings: galaxies: individual — galaxies: Seyfert — gamma rays: general — infrared: sources — ultraviolet: spectra — X-rays: sources

I. INTRODUCTION

The continuum variability of Seyfert galaxies in almost all observable frequency regions is a well-established fact (various contributions to Dyson 1985). For this reason, observations in different energy bands taken at different times have failed to establish the cause-effect relationship in Seyfert flux variations. Elaborate models able to account for the powerful emission observed at any given frequency have been extensively discussed in the literature, but in view of the complex variability pattern, observations taken at different epochs covering as wide a frequency range as possible are needed to discriminate between these models.

NGC 4151, being a classical AGN (active galactic nucleus) prototype, is well suited for this type of analysis, and at least one simultaneous spectrum (radio, infrared, optical, and hard X-ray) has been reported to date (Beall *et al.* 1981). We present contemporaneous infrared, optical, ultraviolet, X-ray and gamma-ray observations of this Seyfert galaxy during mid May of 1980. The observed spectrum, together with variability studies at various wavelengths, is analyzed in order to estimate the properties of the radiation of this Seyfert galaxy.

II. OBSERVATIONS

Most of the observations discussed in this work were obtained as a coordinated effort to study NGC 4151 over a wide energy interval on the occasion of the 1980 May balloon flight of the MISO low-energy gamma-ray telescope. Part of these data have already been reported in the literature and the reader will be referred to the original papers for more detailed information.

Because NGC 4151 lies at a galactic latitude of 75° and has a known emission-line system at $z = 0.0033$, the corrections to the observational data for absorption by galactic material or redshift, or both, are small. There is also little evidence in the ultraviolet data of any smooth depression near 2200 Å attributable to dust absorption in the interstellar medium of NGC 4151, and it is therefore questionable if any extragalactic reddening correction should be applied (Penston *et al.* 1981, but see also Perola *et al.* 1982 for a critical discussion of this problem). The smallest correction corresponds to $E(B-V) = 0.05$ which is a conservative lower limit expected from dust in our own Galaxy toward NGC 4151.

For the remainder of this paper we adopt $E(B-V) = 0.05$ and correct the ultraviolet, optical, and infrared data according to the extinction law described by Seaton (1979) and Glass, Moorwood, and Eichendorf (1982). The journal of all the observations performed in mid May of 1980 is presented in Table 1. Other data collected at a later stage either from the literature or through private communications with the observers have also been used to complement our multi–wave band measurement and are discussed in detail throughout the paper.

a) X-Ray and Gamma-Ray Data

Hard X-ray and low-energy gamma-ray data were obtained with the Milano-Southampton (MISO) telescope (Barker *et al.* 1979) during a balloon flight from Palestine (Texas) on 1980 May 18. The telescope comprises a passively shielded hard X-ray detector (20–180 keV) and a low-energy gamma-ray detector (0.06–16 MeV) having the same field of view (3° × 3°

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TABLE 1

CONTEMPORANEOUS MULTIFREQUENCY OBSERVATION OF NGC 4151

Spectral range	Other Units	Instrument	Date (1980)	Log (Hz)	Log F (mJy [a])	References
Hard X-Ray - Soft γ-Ray ([b])	35 KeV - 16 MeV	MISO	May 18	21.404	-3.256 (2σ u.l.)	This work
				20.910	-2.653 (2σ u.l.)	
				20.557	-2.591 (2σ u.l.)	
				20.284	-2.501 (2σ u.l.)	
				19.942	-2.435 (2σ u.l.)	
				19.536	-2.249 (2σ u.l.)	
				19.276	-2.664 $^{+0.173}_{-0.544}$	
				19.027	-2.190 $^{+0.100}_{-0.128}$	
Soft X-Ray ([b])	2-10 KeV	EINSTEIN (MPC)	May 20	18.103	(-2.07/-2.13) ± 0.002	Perola et al (1982)
Ultraviolet([c])	1150-3200 °A	IUE	May 15	15.314	1.270 ± 0.014	Perola et al (1982)
				15.245	1.624	
				15.164	1.362	
				15.142	1.328	
				15.130	1.279	
				15.095	1.274	
				15.050	1.368	
				15.045	1.361	
				15.014	1.434	
				14.997	1.457	
			May 19	15.314	1.259 ± 0.014	Perola et al (1982)
				15.245	1.284	
				15.164	1.388	
				15.142	1.368	
				15.130	1.366	
				15.095	1.371	
				15.050	1.436	
				15.045	1.419	
				15.014	1.482	
				14.997	1.492	
Optical ([c])	U,B, V	Crimea Observatory	May 17	14.915	1.610 ± 0.008	Lyuty and Rakhimov (1981)
				14.834	1.703	
				14.736	1.837	
Infrared ([c])	J,H, K, L, L'	UKIRT Observatory	May 15	14.380	2.075 ± 0.02	This work
				14.260	2.216	
				14.135	2.317	
				13.933	2.491	
				13.892	2.364	
			May 16	14.380	2.055 ± 0.012	This work
				14.260	2.212	
				14.135	2.333	
				13.933	-	
				13.892	-	
			May 18	14.380	2.067 ± 0.012	This work
				14.260	2.208	
				14.135	2.333	
				13.933	2.499	
				13.892	2.594	

[a] mJy = 10^{-26} ergs cm^2 s Hz.

[b] The frequency has been chosen at the center of the energy channel.

[c] All ultraviolet, optical, and infrared data have been corrected for reddening.

FWHM) and effective areas of 600 cm^2 and 560 cm^2, respectively. The gamma-ray detector consists of two scintillators that form a Compton coincidence detection system inside a semi-active shield.

For this flight, a plastic scintillator NE 102A was used as the upper element of the coincidence system instead of the liquid scintillator NE 311 (boron loaded) used previously. This change was due to a mechanical degradation of the scintillation container. As a consequence of this change, the background of the gamma-ray telescope increased above 1 MeV, reducing the sensitivity by a factor of 2. Five drift scans were performed to survey the region of the sky contained within the coordinate points 23^h12^m and 04^h49^m in right ascension and centered at 39°.6 in declination.

The total observation lasted $\sim$5.5 hr, half of which were spent on the evaluation of the background. During the measurement, the float altitude decreased continuously from 3.5 mbar to 7 mbar, with a mean value during the on-source periods of 5.4 mbar. For the entire observation, the telescope was set at zenith angles varying between 9° and 41°.

In order to avoid adverse effects of systematic variations in the background due to changes in the zenith and azimuth of the telescope, the data for each scan were analyzed separately and the results combined statistically. The only significant source of systematic variation in the background was found to be linearly related to changes in the residual atmospheric pressure. When the data from all five drift scans were combined, no gamma-ray emission from NGC 4151 was detected in the energy range 0.1–16 MeV and only a 3.5 σ excess counting rate was observed in the energy range 35–105 keV.

Soft X-ray (2–10 keV) data were obtained independently from this program by Perola *et al.* (1982) with the *Einstein* MPC (Monitor Proportional Counter) instrument within two days of the MISO observation.

b) Ultraviolet-Optical-Infrared Data

Ultraviolet spectra of NGC 4151 were taken by Perola *et al.* (1982) with the *International Ultraviolet Explorer* (*IUE*) satellite. The observations were made in the low-dispersion mode (effective resolution < 10 Å) using the SWP and LWR cameras. The source was observed using large aperture (10″ × 20″) exposures of either 25 or 45 minutes each. The details of the data reduction are given in Penston *et al.* (1981) and Perola *et al.* (1982).

Optical measurements were taken by Lyuty and Rakhimov (1981), who have kindly made available their contemporaneous photoelectric *UBV* data of NGC 4151, which is observed systematically at the Crimean station of the Sternberg Astronomical Institute. These observations were made with a 60 cm telescope equipped with a photon-counting photoelectric photometer (Lyuty 1977). The aperture used varied between 27″ and 33″.

Because of this big aperture, the *UBV* photometric data are probably contaminated by light from the galaxy surrounding the nucleus and cannot be compared to both ultraviolet and infrared spectral data. To correct for this dependence, the original *UBV* magnitudes have been normalized to a 10″ aperture (similar to that used in the infrared and ultraviolet observations) using an extrapolation based on the aperture dependence obtained by Penston *et al.* (1971, 1974).

In addition, photographic B-magnitudes from the Royal Greenwich Observatory (Gill *et al.* 1984), approximate B band magnitudes from the Fine Error Sensor (FES) on board *IUE* (Perola *et al.* 1982) and multiaperture *UBV* photometry (McAlary *et al.* 1983) are also available for the period 1980 January–May. In order to study the variability of the source over this time interval, all B magnitudes have been reduced to the same RGO scale, using an appropriate correction factor derived by comparing observations taken on the same day or by scaling to the same telescope aperture. To convert magnitudes into fluxes, the absolute calibration of filter bands by Johnson (1966) has been used.

Infrared photometric data of NGC 4151 were taken in 1980 February 7/8 (mean intensities at *J*, *H*, *K*, *L* were 107, 169.5, 222, and 361.5 mJy, respectively) and May (Table 1) with the 3.8 m UK infrared telescope at Mauna Kea (Hawaii) using an InSb photometer. The aperture used was 10″.8. Additional infrared photometric measurements during the observing period were taken by Balzano and Weedman (1981) and by McAlary *et al.* (1983) using different apertures of 10″.3 and 7″.9, respectively.

Since the few μm flux of NGC 4151 is not strongly dependent on the aperture size (for apertures ranging from 5″ to 10″ (Penston *et al.* 1971, 1974)) we have not attempted to normalize the McAlary *et al.* data to a 10″ aperture. To convert the infrared magnitudes into fluxes, we have used the calibration of *JHKLM* photometry of Wamstecker (1981) except for *L* (3.85 μm) for which the calibration of Gehrz, Hackwell, and Jones (1974) has been adopted.

III. RESULTS

The reported observations provide data on the spectrum and variability of the radiation from NGC 4151 over a wide range of frequencies before and during the X-ray and gamma-ray observation.

The MISO 1980 data set, including the (2–10) keV spectral point (calculated from the reported MPC flux assuming a spectral index $\alpha_x = 0.5$) is shown in Figure 1, where the *HEAO 1* A4 (1977 and 1978 December, 1978 June) and *OSO 7* (1973 April–May) observational data from Baity *et al.* (1984) are also plotted for comparison. Despite the possibility that the 2–10 keV flux varied on a time scale of a few days (Lawrence 1980), the combination of the MPC and MISO points seems to indicate a photon spectrum similar both in intensity and in spectral shape to those observed in mid 1973 and mid 1978, when the source intensity at 100 keV was close to the weighted average of all the hard X-ray observations reported to date ($\sim 3 \times 10^{-5}$ photons cm^{-2} s keV; Baity *et al.* 1984). In all three sets of data, the spectrum seems to steepen at energies above 50 keV, indicating either a spectral break or that a source spectrum more complex than a single power law must be assumed. On the other hand, the *HEAO 1* A4 combined spectra from 1977 and 1978 December, when the source was slightly less intense, are best fitted by a single power law ($\alpha_x = 0.6$; Baity *et al.* 1984).[2]

Two previous observations with the MISO telescope in 1977 and 1979 positively detected NGC 4151 at gamma-ray energies up to a few MeV (Perotti *et al.* 1979, 1981). These measurements favor a slightly harder power-law spectral fit (α_x close to 0) and give evidence for the presence of a spectral break or rollover starting at $\sim$1 MeV (considerably higher than the 50 keV break mentioned above).

[2] In this paper, we represent the energy spectral index by α, such that $F_\upsilon \propto \upsilon^{-\alpha}$. The photon spectral index Γ is related to α by $\Gamma = \alpha + 1$.

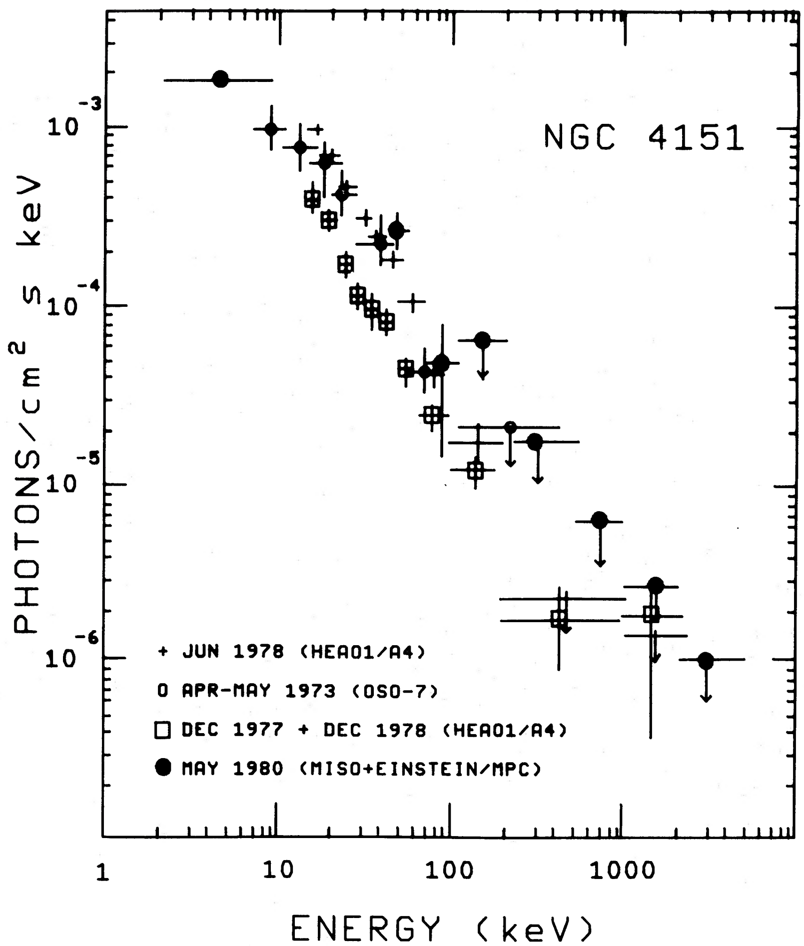

FIG. 1.—Photon spectrum observed by the MISO and MPC telescopes from NGC 4151 in 1980 May. Spectral data from the *HEAO 1* A4 and *OSO 7* instruments are also shown for comparison. All upper limits obtained at gamma-ray energies correspond to a 2 σ confidence level.

Despite the reduction in sensitivity of the detector for this 1980 balloon flight, the lack of a positive detection of the source in the MeV region supports the variability previously detected by the same telescope (Perotti *et al.* 1979, 1981).

The overall infrared-optical-ultraviolet spectrum of NGC 4151 as measured in 1980 May is shown in Figure 2*a*. The ultraviolet flux distribution in the interval $2200 < \lambda < 3000$ Å can best be described by a power law with spectral indices varying between $\alpha_{uv} = 1.47 \pm 0.2$ (May 15) $\alpha_{uv} = 1.03 \pm 0.14$ (May 19). The extrapolation of this power law continuum to $\lambda < 2200$ Å falls below the measured flux values, indicating the presence of a short-wavelength excess. Comparing the two sets of UV data, it is evident that the flux increase at $\lambda = 2500$ Å of $\sim 25\%$ going from May 15 to May 19 was accompanied by a slight hardening of the spectrum, while the excess above the power law decreased by a factor of 3 during the same period (for an extensive discussion on this excess the reader is referred to Perola *et al.* 1982).

At longer wavelengths ($\lambda > 3000$ Å), the *UBV* fluxes obtained on May 17, are consistent with the extrapolation of both ultraviolet spectra (from the *UBV* data alone $\alpha_{op} = 0.96 \pm 0.1$). When a single ultraviolet-optical slope is calculated in the wavelength range 2200–6200 Å, we find α_{op-uv} to be ~ 1.2.

Within the errors, the three sets of infrared spectral data are identical and can best be fitted by a power law of index $\alpha_{ir} = 1.03 \pm 0.1$. Despite the similarity in spectral slopes between the visual and infrared bands, the overall infrared-optical distribution requires the presence of a spectral inflection at 0.5–1.5 μm. This is better defined in Figure 2*b*, where we have plotted the infrared-optical-ultraviolet spectrum of the source during 1980 April 16–23 (McAlary *et al.* 1983; Perola *et al.* 1982). The broad-band "bump" noticeable in the figure is probably due to contamination from the emission lines in the spectrum. This is most easily seen in the R band, where the Hα emission contributes a significant proportion of the emitted flux.

Infrared, optical, and ultraviolet light curves are shown in Figure 3 for the period 1980 January–May. At the beginning of 1980 May, the source was recovering from a deep minimum which occurred around mid April of 1980 and was most noticeable at ultraviolet frequencies. The rapid increase observed by *IUE* from May 15 to May 19 was part of this general trend. The ultraviolet brightening by approximately a factor of 3 (at 2500 Å) to 5 (at 1455 Å) over a month was accompanied by a 50% flux increase in the optical B band and 10% in the infrared 2.2 μm band. However, given the uncertainty introduced by comparing data from different instruments, evidence for source variability of less than few tens of percent should be regarded with some caution. We conclude that the most extreme variability occurred at the shortest wavelengths and that the scale of the variations decreased steadily toward the longest optical wavelengths. This corresponded to a spectral flattening of the optical-UV source profile by $\Delta\alpha = 1$ over a

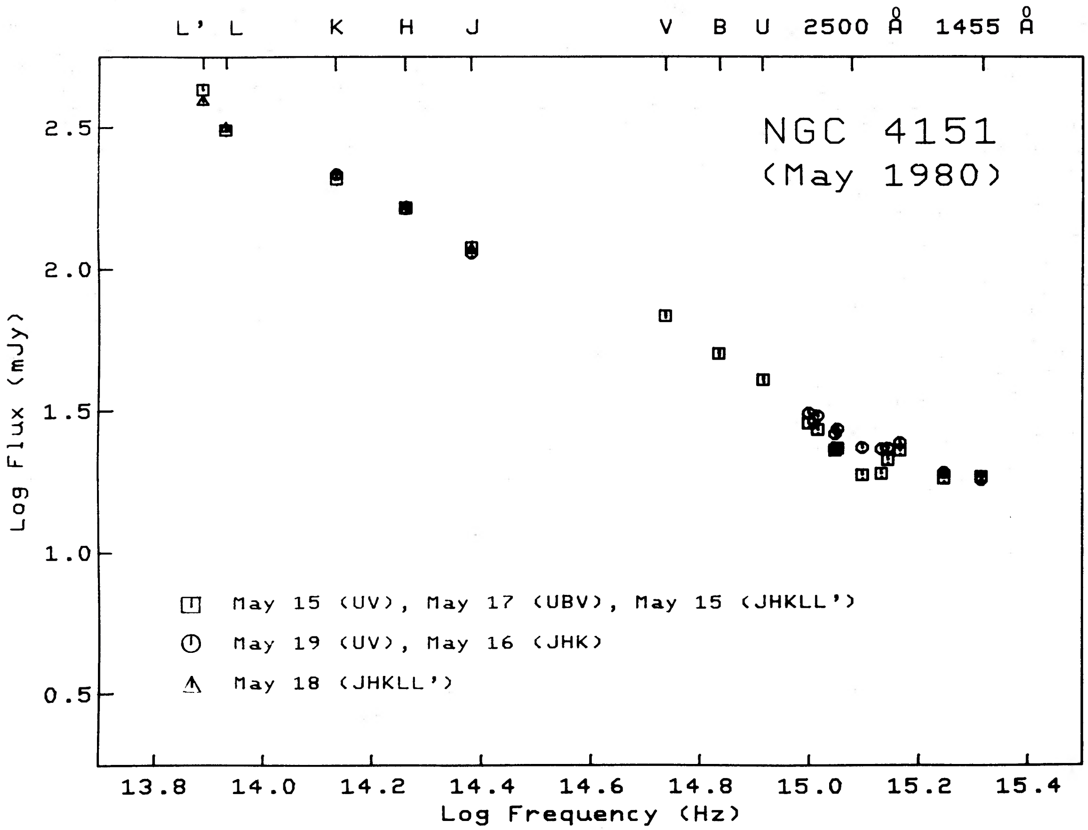

FIG. 2*a*

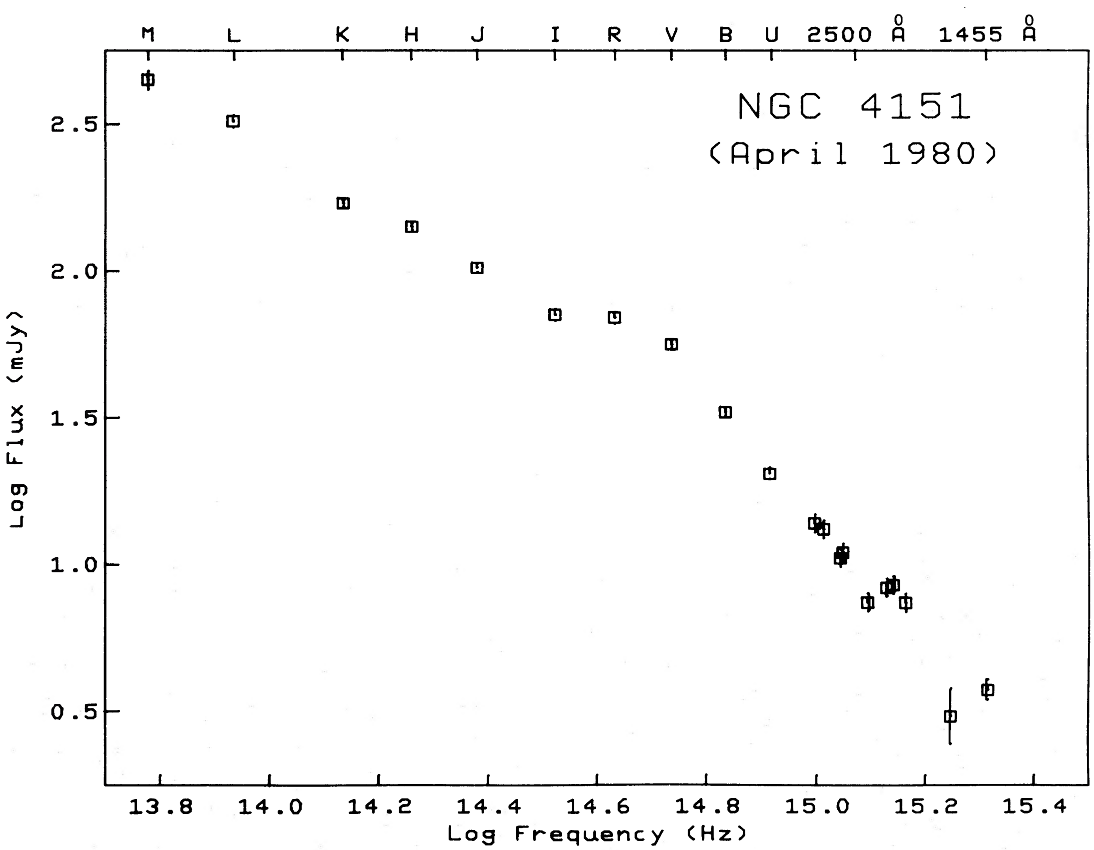

FIG. 2*b*

FIG. 2.—Near-infrared, optical, and ultraviolet spectrum of NGC 4151 during the period 1980 May 15–19 (*a*) and April 16–23 (*b*). Error bars are shown only when the flux uncertainty exceeds the size of the symbols used.

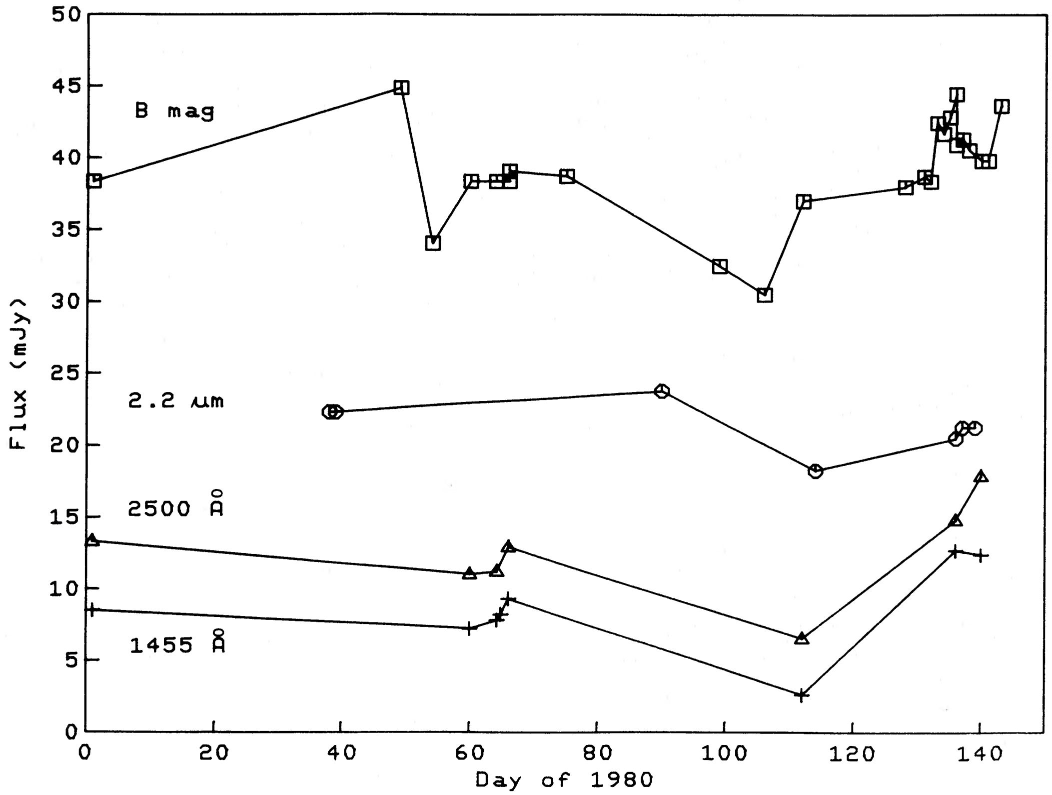

FIG. 3.—The long-term variability of NGC 4151 at ultraviolet (1455 Å, and 2500 Å), optical (photographic B mag) and near-infrared (2.2 μm) frequencies during the period 1980 January–May. For reason of representation, the 2.2 μm flux values have been divided by a factor of 10.

time scale of a month, while the infrared source profile remained substantially unchanged. Also the data suggest that there were no conspicuous time delays between the variations observed at different wavelengths in the ultraviolet-optical continuum. This indicates that the variable ultraviolet-optical continuum emission arises from a single source region.

On the other hand, the lack of spectral or even intensity variations at a few μm and the spectral inflection seen in the transition region from optical to infrared frequencies both suggest that most of the near-infrared luminosity in NGC 4151 is produced by a source component distinct from that which dominates the optical-UV spectra. This conclusion is further supported by the different variability times scales observed in the two bands (10–20 days in optical-UV [Perola *et al.* 1982] and months in infrared [Cutri *et al.* 1981]).

The wavelength dependence of the amplitude variation seen in the optical-UV band would be explained if the variable source dominates the UV emission but contributes a progressively smaller percentage toward the longest wavelengths. In this case, the intrinsic spectrum of the variable source can be determined by subtracting the spectra observed at different epochs (Cutri *et al.* 1985). The result of this subtraction is shown in Figure 4, where the spectrum found is also compared to that obtained by Rieke and Lebofsky (1981) using a decomposition technique based on various types of observational data.

The two spectral profiles are in good agreement, suggesting that although the spectrum of this variable component may be changing in intensity, it remains constant in shape. The vertical arrows in Figure 4 give an indication of the amplitude of the intensity variability. Note also that continuum polarization of NGC 4151 in the range 3700–7100 Å is wavelength dependent: it varies smoothly from a value of 1.2% in the red to a maximum value of 2.5% at 4000 Å, declining rapidly at shorter wavelengths (Schmidt and Miller 1980).

The errors associated with the flux values plotted in Figure 4 are evaluated by statistically combining the errors on the individual data points (typically between 3%–9%) and do not take into account the measurement systematic errors. These errors may be particularly relevant at infrared wavelengths where the observed intensity variation is of the order of only a few percent. Note that the excess emission near 3000 Å mimics the shape of the " bump " found in the spectra of many QSOs (Oke, Shields, and Koryconsky 1984).

Alternatively, the optical-UV variations of different amplitude may be due to changes in the spectral energy distribution of a single source arising, for example, from fluctuations in the high-energy electron spectrum responsible for synchrotron emission (Cutri *et al.* 1985). In this case, at least at maximum light, the variable source appears to dominate the total output in the blue and ultraviolet. The optical-UV spectrum flattens with increasing brightness and at maximum may have a slope $\alpha = 0.6$ (Perola *et al.* 1982).

In either case, the variable optical-UV continuum source has a flat spectrum. In the presence of electron energy losses, this shape cannot be easily produced at these frequencies with simple synchrotron-Compton emission models (Kardashev 1962). Mechanisms other than pure synchrotron emission need to be considered for the production of the optical-UV continuum (Cutri *et al.* 1985).

IV. THE OVERALL SPECTRAL PROFILE

The composite spectrum of NGC 4151 from radio to gamma-rays is plotted in Figure 5. Archival radio and far-

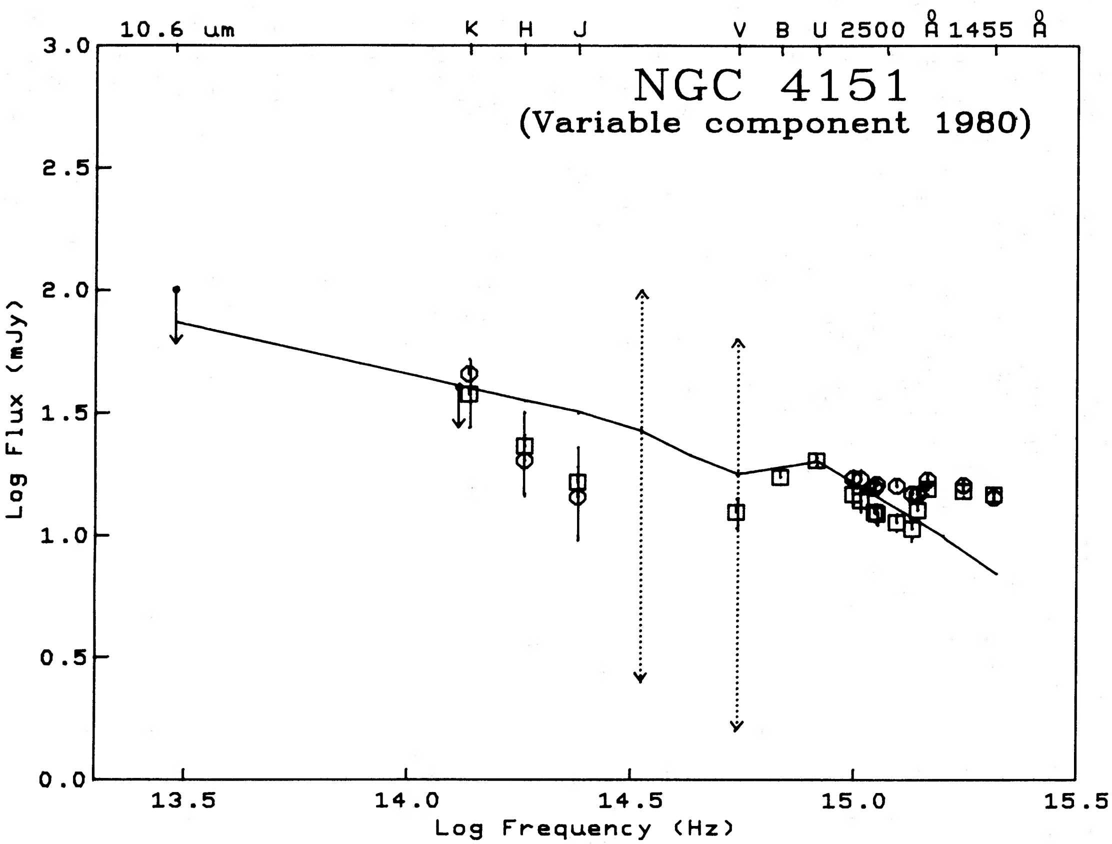

FIG. 4.—Intrinsic spectrum of the variable optical-ultraviolet source determined by subtracting spectra observed one month apart. Error bars are shown only when they exceed the size of the symbols used. The solid line represents the spectrum of the "highly variable nonthermal" source of Rieke and Lebofsky (1981). The vertical arrows at the V and I magnitude points show the amplitude of the variability.

infrared data are also shown for completeness. In view of the lack of variability so far reported at radio frequencies (Coe *et al.* 1983) and because of the paucity of far-infrared data, we adopt these observations as valid for the epoch of our multi-waveband study. When combined with the 1980 May data, they show that the source profile from 9×10^{12} Hz to 2×10^{15} Hz is, to a first approximation, consistent with a single power law of index $\alpha = 1$. Broad-band bumps are, however, superposed on this underlying power-law distribution as a reminder that more than one simple emission mechanism is at work in the source (refer also to § III on this point).

In particular, we note that recent *IRAS* observations of a few Seyfert galaxies indicate that the near-infrared power-law emission extrapolates into the far-infrared (up to 100 μm) maintaining the same spectral slope (Spinoglio *et al.* 1985). At radio frequencies the emission of NGC 4151 is severely weakened: the radio flux intensity is far below any extrapolation from the far-infrared continuum and has a flatter spectral index ($\alpha_r = 0.8$; Ulvestad, Wilson, and Sramek 1981).

There are various ways in which the radio emission from a Seyfert may be absorbed but only two are consistent with the observational constraints: synchrotron self-absorption and free-free absorption (Spinoglio *et al.* 1985). In the first case, applying the formalism of Condon *et al.* (1981) and taking the lowest infrared frequency ($vo = 8955$ GHz, $F_{vo} = 4300$ mJy, where $F_v \propto v^{-1}$) and the highest radio frequency ($vr = 10.7$ GHz, $F_{vr} = 71$ mJy) at which the spectrum of NGC 4151 has been measured, we obtain that the size of the self-absorbed region is $\theta \approx 0.03$ milli-arcsec (a value not strongly dependent on the particular choice of parameters and insensitive to the value of the spectral index α for $\alpha <= 1$). In the limit $z \ll 1$, this value corresponds to a light travel time of $\sim tv$ (days) $= (3.65 \times 10^4)\ z \times (50/H_0) = 3$–4, which is well outside the range of variability time scales observed in the near-infrared (Cutri *et al.* 1981) and similar to the range observed at X-ray wavelengths (Lawrence 1980). On the other hand, the radio emission may be free-free absorbed by the gas clouds associated with the broad-line region (BLR), which in NGC 4151 is located at $R = 10^{17.7 \pm 0.4}$ cm (Bromage *et al.* 1985) and therefore is probably coincident with the infrared region. In this case, for reasonable values of the BLR cloud parameters (Ferland and Mushotzky 1982), we expect to see a low-frequency turnover at $\log v = 11.7$–12.7, in agreement with the observed upper limits. Further observations in the unexplored far-infrared–mm region may shed some light on some of these points.

At short wavelengths (X-ray region), the energy distribution becomes flatter than $\alpha = 1$, although an extrapolation of the optical–UV power law is roughly consistent with the few keV intensity. Above 50 keV the spectral profile is less clearly defined and may be highly variable. The two most likely mechanisms put forward to explain the observed X-ray spectral characteristics are (1) unsaturated thermal Comptonization and (2) nonthermal Compton upscattering of self-target photons generally assumed to be produced via the synchrotron mechanism. In the first case, thermal Comptonization is not able to reproduce the high-energy spectral shape observed occasionally in NGC 4151 (Baity *et al.* 1984).

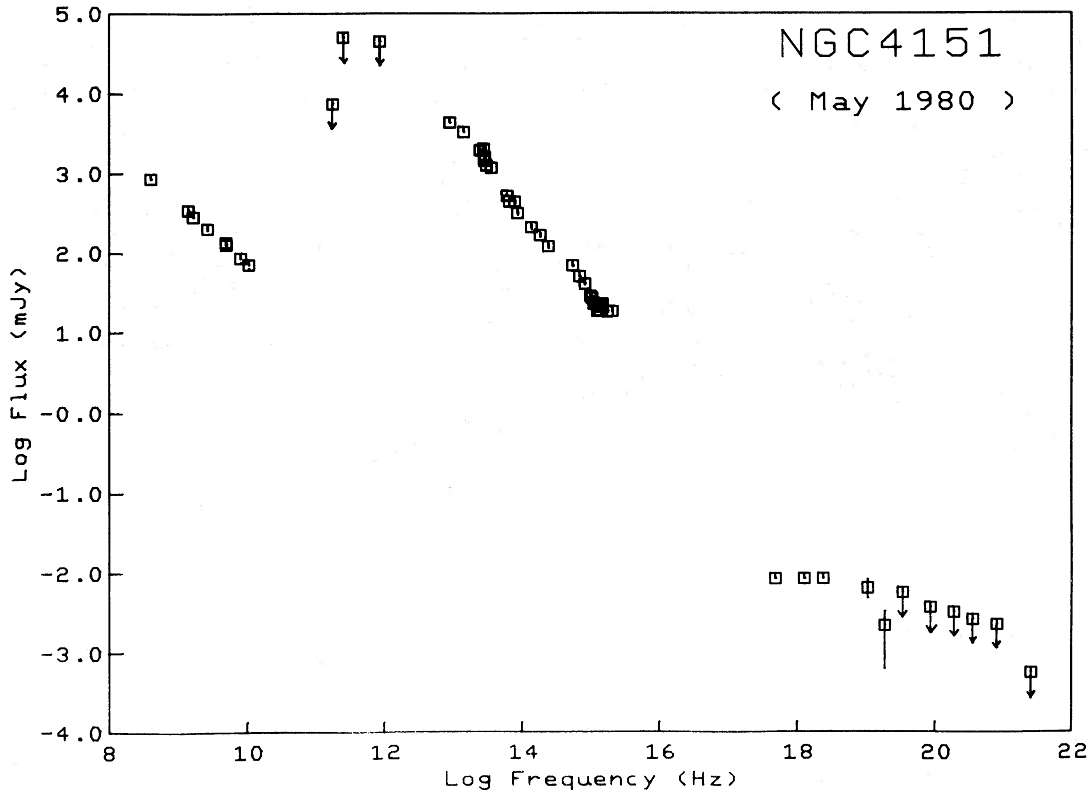

FIG. 5.—Combined absolute spectral energy distribution of NGC 4151 from X-ray/gamma-ray to near-infrared wavelengths based on the observations performed in 1980 May (Table 1). Archival radio and far-infrared data are also shown for completeness. Going from low to high frequencies, the data are taken from the following references: Fanti *et al.* (1973); Wilson and Meurs (1982); Booler, Pedlar, and Davies (1982); Beall *et al.* (1981); Ulvestad *et al.* (1982); Coe *et al.* (1983); Clegg, Ade, and Rowan-Robinson (1974); Baity *et al.* (1975); Gezari, Schmidt, and Mead (1984).

In the second case, it is difficult to explain why the X-ray emission has a flatter spectral slope and faster variability time scale than the emission at other wavelengths. If, however, the continuum emission at wavelengths longer than 50 μm is observed to flatten, it may be taken as the target radiation for Compton scattering of photons to X-ray energies.

On the other hand, it is difficult to discriminate between various other models proposed to explain the X-ray emission, particularly in the high-energy (hard X-ray/soft gamma-ray) band, where we lack observational details. The observations performed so far have indicated that the continuum emission at these wavelengths is far more complex than previously known and that high-resolution/high-sensitivity monitoring studies are badly needed before any conclusions as to the emission mechanism can be drawn. It is also very important that future observations of this source cover more extensively the less explored parts of the electromagnetic spectrum such as the far-infrared–mm regions. Furthermore, simultaneous observations in different energy bands over several months would be helpful in determining the relationship between the various components which produce the composite spectrum from radio to gamma rays.

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