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SPECTRAL COMPONENTS AT VISUAL AND INFRARED WAVELENGTHS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

We present aperture-dependent infrared photometry of active galactic nuclei which illustrates the importance of eliminating starlight of the galaxy in order to obtain the intrinsic spectral distribution of the active nuclei. Separate components of emission are required to explain the infrared emission with a spectral index of $\alpha = 2$ and the typical visual-ultraviolet continuum with $\alpha = 0.3$ (where $F(\nu) \propto \nu^{-\alpha}$). Present evidence does not allow us to uniquely determine the appropriate mechanisms, but the characteristics of each are discussed.

Key words: Galaxies--Infrared Observations

I. INTRODUCTION

A subject of considerable ongoing mystery is the physical origin of the continuum radiation observed at visual and infrared wavelengths from active galactic nuclei (AGN). The 10^{13}- to 10^{15}-Hz (0.3- to 30-μm) continuum has been observed for many years and yet, the origin of the ultraviolet, visual, and infrared continuum is not known with certainty for most objects. The same statements can be made about QSOs, in general, although we think that in the case of OVV quasars and BL Lac objects, the origin of the continuum is to be explained through the synchrotron self-Compton mechanism (Jones et al. 1974).

On the other hand, there is general agreement on the interpretation of the origin of infrared emission in some AGNs such as NGC 1068. The combined information of spectral-flux distribution and size of the emission region lead to the conclusion that the 1- to 10-μm radiation originates in thermal emission by dust in the nucleus of the galaxy (Becklin et al. 1973; Jones et al. 1977). The origin of the visual and ultraviolet continuum is less well understood, but evidence suggests that there is a rather flat nonstellar component that provides photoionizing light for excitation of the emission-line clouds in this object (Neugebauer et al. 1980). The continuum is strongly polarized after correction for starlight (Miller and Antonucci 1983), and this component may have a relatively steep spectral distribution compared to the total light.

We are faced with a situation in which we think that we understand the origin of the optical-infrared continuum observed from some objects, but cannot rely on these interpretations to apply in general for all AGNs and QSOs. A striking example of the controversy over the origin of infrared radiation from AGNs is the case of NGC 4151. Observational results are interpreted by Rieke and Lebofsky (1981) as indicating that most of the 10 μm radiation from this object is thermal emission by dust, whereas Ferland and Mushotzky (1982) argue that, although some reddening is present, "the infrared excess is not the reemission of energy absorbed from the high-energy power-law continuum." Malkan and Filippenko (1983) also conclude that the short-wavelength infrared radiation of NGC 4151 is not attributable to thermal emission by hot dust grains.

In this paper, we present data to show that in a very small aperture where the contribution of starlight from around the active nucleus is minimized, the common characteristic of a rather steep infrared continuum emerges ($F(\nu) \propto \nu^{-2}$), as compared to that at visual wavelengths in most objects. This characteristic spectral shape is similar to the continuum observed from many emission line QSOs that do not exhibit OVV properties. By comparison, in those objects with a strong nonthermal continuum, an infrared cutoff can result in a steep visual spectral distribution (Rieke et al. 1982). We also objectively review the emission mechanisms that may contribute to ultraviolet, visual, and infrared emission from AGNs and QSOs in order to help guide future investigation of these problems with the aim of ultimately determining the physical processes involved.

II. OBSERVATIONS AND RESULTS

Multiaperture photometry of NGC 1275, 3C445, IZw1, Mrk 335, and 3C120 were obtained with the NASA Infrared Telescope Facility (IRTF) on Sept. 13–14, 1981 UT using the standard InSb photometer. On an earlier date, Oct. 26, 1980 UT, Mrk 509 was also observed. π^4 Ori was used as a primary standard with adopted magnitudes at J, H, K, and L of 4.06, 4.08, 4.13, and 4.14, respectively. Both π^4 Ori and a secondary standard, ρ Peg, were observed through the same set of apertures as the galaxies. This allowed us to monitor the seeing and also to correct for the light lost in the small apertures.

The data for the galaxies were reduced in the normal fashion using observations of the galaxy and the standard star measured through the same aperture. The reduced data are shown in Table I, except for those of NGC 1275, which have been previously published by Longmore et al. (1983). For a point source at the nucleus of a galaxy, this reduction procedure ensures that the light lost in the small apertures is taken into account. Figure 1 shows the results for NGC 1275 since it is particularly illustrative. At the long wavelengths, the flux from the central source (not the galaxy) dominates; thus at L the flux density is constant with aperture size. At J, H, and K, the contribution from starlight is significant and it dominates at the largest apertures. We do not show the aperture-dependent plots for all objects because they are similar to those of Figure 1. Rather, the resulting photometric spectral distribution of the compact nuclear source derived from the aperture-dependent studies are shown in Figure 2. These spectral distributions of the intrinsic active nucleus are to be compared with those derived by Penston et al. (1974). We note that our sample of objects includes both those that are radio loud (N1275, 3C120, 3C445) as well as those that are weak at low frequencies (IZw1, MK335). Visual wavelength spectral distributions that have not been obtained by eliminating galactic starlight are irrelevant to this discussion.

We have not had the opportunity in this investigation to obtain aperture-dependent data in order to eliminate starlight from the galaxy surrounding the active nucleus at wavelenghts less than 1.0 μm. De Bruyn and Sargent (1978) present optical data for the radio quiet objects. Allowing for the blue bump, the spectral indicies are approximately 1.1, 0.5, and 0.9 for IZw1, Mrk 335, and Mrk 509, respectively. Only for Mrk 509, which has the bluest infrared colors in our sample, is there a relatively smooth merger between the optical and near-infrared, in agreement with the results of Malkan and Filippenko (1983). The radio-selected objects display much steeper spectra ranging from 1.6 for 3C120 (Shields, Oke, and Sargent 1972) up to 2 for NGC 1275 and 3C445 (De Bruyn and Sargent 1978; Yee and Oke 1978). However, the spectra of 3C120 and 3C445 are known to be reddened (Lacy et al. 1982; Rudy and Tokunaga 1982), while there is a substantial contribution from starlight in the case of NGC 1275 (Longmore et al. 1983). The reddening and the contribution from starlight diminishes rapidly beyond 1 μm such that we again are confronted with a spectral break between the unreddened, nonstellar optical continuum and that of the infrared.

We therefore have the challenge of explaining the change in slope of the continuum of many active nuclei from $\alpha \approx 2$ at wavelengths longer than 1 μm to one that is rather flat at visual wavelengths. This observed characteristic is also typical of many emission-line QSOs (Neugebauer et al. 1979) that are not OVVs. The outstanding example of an object exhibiting this spectral change is the radio-loud QSO 3C273.

III. DISCUSSION

Among the brightest and best-studied examples of objects similar to those in our study that exhibit the characteristic change in slope of the continuum at $\lambda \sim 1$ μm (when galactic light is eliminated) are the active nucleus of the Seyfert galaxy NGC 4151 (Rieke and Lebofsky 1981) (a relatively radio-quiet object) and the QSO 3C273 (Worrall et al. 1980) (a radio-loud object). In this discussion, we address those emission mechanisms potentially responsible for the radiation in the wavelength range 0.3–20 μm. Recent studies of the longer wavelength emission ($\lambda > 30$ μm) have concluded that in some cases cold dust is responsible for the radiation observed (Jones et al. 1977; Telesco and Harper 1980), and in some cases (some radio-loud objects) the extrapolation of the nonthermal high-frequency radio emission is sufficient to explain the infrared as well (Jones et al. 1981).

A. Potential Flat Visual-Ultraviolet Emission Mechanisms

The question of the physical origin of the visual-ultraviolet continuum was addressed by DeMoulin and Burbidge (1968). They discussed synchrotron emission and Compton scattering as possible origins of the flat power law spectrum required. Indeed, recent studies of polarization as a function of wavelength with high spectral resolution generally confirm the existence of a flat power-law component of polarized emission in the observed spectrum of NGC 4151 (Schmidt and Miller 1980).

Another possible origin of the visual-ultraviolet continuum has been suggested by Shields (1978)—thermal emission by the optically thick accretion disk of a supermassive compact object. Indeed, recent supportive observational evidence has been offered in connection with analysis of the nature of the so-called blue bump that is present at blue and ultraviolet wavelengths (Malkan and Sargent 1982; Malkan 1983). However, the other potential explanation of the blue bump is the extrapolation of the power-law component to which is added Balmer continuum emission (Puetter et al. 1982).

It therefore seems that there are three possible explanations for the flat visual-ultraviolet continuum that may realistically be considered: synchrotron emission, Compton scattered emission from lower frequencies, and emission from an optically thick accretion disk. Any of these mechanisms may be used to explain a relatively flat power-law visual-ultraviolet continuum. The situation that frequently arises in astrophysical problems prevails here—it is easy to list the possibilities, but it is not so easy to come to definitive conclusions about which hypothesis is correct.

DeMoulin and Burbidge (1968) considered the generation of nonthermal optical emission in AGNs and QSOs and concluded that electron synchrotron radiation was the most likely process involved. The BL Lac objects (Stein et al. 1976) are clear examples of sources of this type. The problem with interpreting the flat photoionizing continuum of AGNs and QSOs as Compton scattered radiation is that of the low flux of radio emission observed from several of the sources (e.g., especially radio-quiet QSOs) requires that most of the luminosity by large factors be in the form of the Compton scattered radiation. In the radio-loud objects, the possible Compton origin seems more plausible. However, we must then question why the flat photoionizing continuum of a radio-loud object such as 3C273 is so similar in character to that of a relatively radio-quiet object such as NGC 4151. Radio-loud and radio-quiet objects are similar in spectral distribution for $\nu > 10^{13}$ Hz (Neugebauer et al. 1979; Capps et al. 1982) and perhaps for $\nu > 10^{12}$ based on recent IRAS data (Neugebauer et al. 1983). Therefore, a Compton scattered origin of optical continuum would require scattering of infrared photons to the visual-ultraviolet part of the spectrum (DeMoulin and Burbidge 1968). We would then expect that since the visual-ultraviolet emission varies strongly (e.g., NGC 4151) the infrared emission would as well. Infrared monitoring of even the brightest QSOs and AGNs has been sporadic, but if anything can be said, it is that in NGC 4151 variability is less pronounced in the infrared than at visual-ultraviolet wavelengths (Stein et al. 1974; Penston et al. 1974; Lyutyi et al. 1977). This is true for other active galaxies and quasars as well (Rieke and Lebofsky 1979; Cutri and Wisniewski 1983). We therefore conclude that Compton scattering from the infrared to visual-ultraviolet wavelengths is probably not the explanation of the photoionizing continuum.

We cannot rule out emission from a thermal accretion disk as a means of explaining the flat continuum at these wavelengths. The resulting emission could be variable, as is observed in some AGNs, due to a changing accretion rate, and it might be polarized by scattering. Additional studies of variability and polarization in the blue bump are required.

B. Potential Explanations of the Infrared Continuum

The impossible explanations of the infrared continuum of AGNs and QSOs have been discussed originally by Burbidge and Stein (1970). They analyzed physical parameters and consequences of emission by relativistic electrons (synchrotron radiation) and thermal reradiation by dust grains. Nonthermal infrared emission would be variable on short timescales, whereas thermal reradiation at these wavelengths would not vary on short timescales.

Another possible mechanism has been suggested as an explanation of the infrared emission by Ennis et al. (1982). Compton thermalization of infrared seed photons by a hot plasma ($T \sim 10^{9°}$ K) has been suggested to produce a quasi power-law infrared continuum in an application of a suggestion by Katz (1976) and others. Presumably, the infrared radiation resulting from this process would not vary in time on short timescales since it would originate in the hot, extended low-density region of a QSO.

Puetter and Hubbard (1984) suggest that a strong contribution of near-infrared free-free emission could account for the strong $\lambda \sim 3$ μm emission of QSOs. Their suggestion depends strongly on exceedingly high densities ($n_e > 10^{11}$ cm^{-3}) in the emission-line clouds. Such densities are in conflict with constraints on electron density ($n_e < 10^{10}$ cm^{-3}) imposed by other investigators (e.g., Kwan and Krolik 1981) on the basis of theoretical spectroscopic models. It is not possible for us to comment further on the discrepancies between the results of these computer-generated models of various investigators. It is a matter of some priority that these disagreements be resolved.

Malkan and Filippenko (1983) argue for the absence of a strong near-infrared thermal dust component in Seyfert 1 galaxies. This analysis, based upon six objects, pivots upon the detection, after the removal of starlight, of a component that smoothly spans the optical/infrared region with a typical slope of ~-1.1 to -1.2. This clearly is not the case for our sample, and the reason for this discrepancy is not known.

One indirect argument that thermal emission dominates in at least spiral AGNs is that the similarity of the spectra at 1-3.5 μm (see Figure 2) provides evidence that the physical conditions are the same in all of these objects. This result can be understood if it is assumed to be emission from hot dust that has been heated by an exciting source at the galactic nuclei. This "thermalized" emission would then be insensitive to the nature of the exciting source; thus, similar near-infrared spectra can be generated by exciting sources of different properties (radio-loud versus radio-quiet, for example). Observations of the broad-line radio galaxy 3C234, for example, show a power-law spectrum at 1-3.5 μm and a break at 5 μm, which is interpreted as an indication of thermal emission in the near-infrared (Carleton et al. 1983). Small aperture 1- to 10-μm spectra of other AGNs could help to settle this question if spectral breaks can be observed near 5 μm as in 3C234.

We see from the available evidence that in some cases dust reradiation is appropriate and in other cases synchrotron emission is the proper explanation. We do not think that the Compton thermalization process need be invoked to explain infrared emission from AGNs and QSOs. In fact, since the forbidden-line regions of these objects are not optically thick to electron scattering, only a small fraction of the seed photon energy at lower frequencies could be redistributed to higher frequencies by this process, and we still must invoke a physical process to generate the majority of the luminosity at lower frequencies. The physical processes that can naturally be responsible for these seed photons are synchrotron emission and dust reradiation. We are forced back to the same processes to generate the majority of the luminosity whether or not we invoke Compton thermalization to produce a higher frequency spectrum.

C. Summary

It would seem that the available evidence required to explain the change in slope of the continuum at infrared wavelengths to that at visual wavelengths leaves considerable room for further investigations and documentation to resolve these questions of physical origin. The likely possible explanations of the visual-ultraviolet continuum are synchrotron emission (SV) and thermal accretion (A) while the probable origins of the infrared ($\lambda < 20$ μm) are synchrotron (SIR) and dust reradiation (D). A complete explanation of the origin of the 0.3- to 30-μm continuum would presently seem to involve four possible combinations: SV + SIR (two possible separate nonthermal components), SV + D (a nonthermal source imbedded in a dust cloud), A + SIR (both thermal accretion and an infrared nonthermal component), and A + D (a combination requiring only thermal processes).

It will take some time to obtain observational evidence to distinguish between these possible alternatives. A comprehensive study of variability characteristics of a number of sources of various types must be carried on for a number of years. Angular size measurements in the infrared will require further development of infrared interferometry techniques. Finally, the detection of spectral features indicative of dust in infrared emission may not be possible until extensive spectra can be obtained from above the terrestrial atmosphere from SIRTF.

IV. CONCLUSIONS

Aperture-dependent infrared observations of AGNs obtained to eliminate the starlight contribution in the galaxy show that a change in slope of the active continuum of the nucleus from visual-ultraviolet wavelengths to $\alpha \approx 2$ at near-infrared wavelengths is necessary for many objects. This characteristic is similar to that observed from many QSOs. Two physical components of emission are therefore necessary at infrared and visual wavelengths. The likely origins of the visual-ultraviolet emission are synchrotron radiation and a thermal accretion disk. The likely origins of the near-infrared emission are synchrotron radiation and thermal reradiation of dust. We are left with four combinations of explanations for the combined infrared-visual spectral distribution among which the present available evidence does not allow us to distinguish. Each object must be treated individually in this regard.

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TABLE I

FLUX DENSITIES OF THE MEASURED GALAXIES

Date (UT)	Object	Aperture	f_ν(mJy) J	H	K	L
1980 Oct 26	Mrk 509	5.3″	18.7	30.9	44.4	84.2
1981 Sep 13	3C 445	1.9″	-	-	-	44.4
"	"	3.5″	5.08	10.1	19.5	48.1
1981 Sep 14	IZw1	3.5″	17.6	33.1	57.0	124.
1981 Sep 14	3C 445	3.5″	4.76	9.90	18.2	47.4
"	"	5.3″	5.12	10.1	19.2	48.7
1981 Sep 14	Mrk 335	3.5″	15.8	28.6	50.6	108.
"	"	5.3	17.2	30.8	51.8	113.
"	"	7.5	17.8	32.1	53.3	117.
"	"	8.9	18.6	33.4	54.4	-
1981 Sep 14	3C 120	1.9″	9.19	16.1	28.3	71.3
"	"	3.5	10.2	17.1	28.6	65.8
"	"	5.3	11.7	19.2	30.4	63.0
"	"	7.5	13.2	22.1	33.3	65.5
"	"	8.9	13.9	23.5	35.1	-
"	"	10.3	14.8	24.6	36.2	-

Note: All statistical 1σ errors are less than 4% and typically less than 2%.

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FIGURE CAPTIONS

Fig. 1—Aperture-dependent flux measurements from NGC 1275, adapted from Longmore et al. (1983). At 1-25 μm (J, H, K), the stellar flux dominates, and it decreases with decreasing aperture. At 3.5 μm (L) the flux is nearly all from the central source of the galaxy and is unresolved.

Fig.2—Data on galaxies observed. Only the observations in the smallest apertures are shown to minimize the contribution from the stars. The aperture size is shown in parentheses. Note the change of the flux scale by a factor of 2 for Mrk 509.

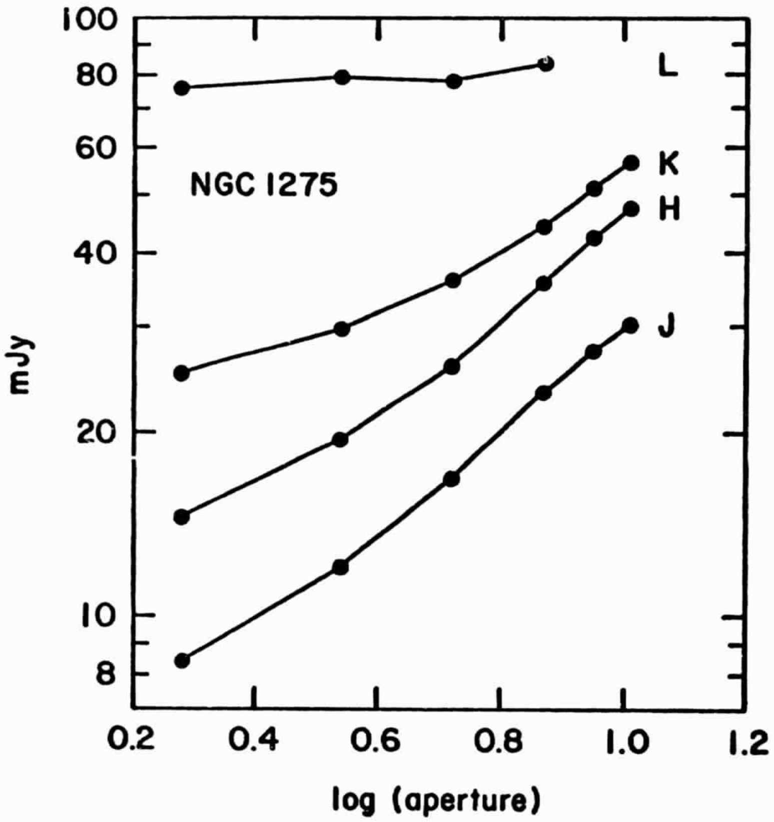
NGC 1275
mJy
100
80
60
40
20
10
8
L
K
H
J
log (aperture)
0.2
0.4
0.6
0.8
1.0
1.2

Fig. 1

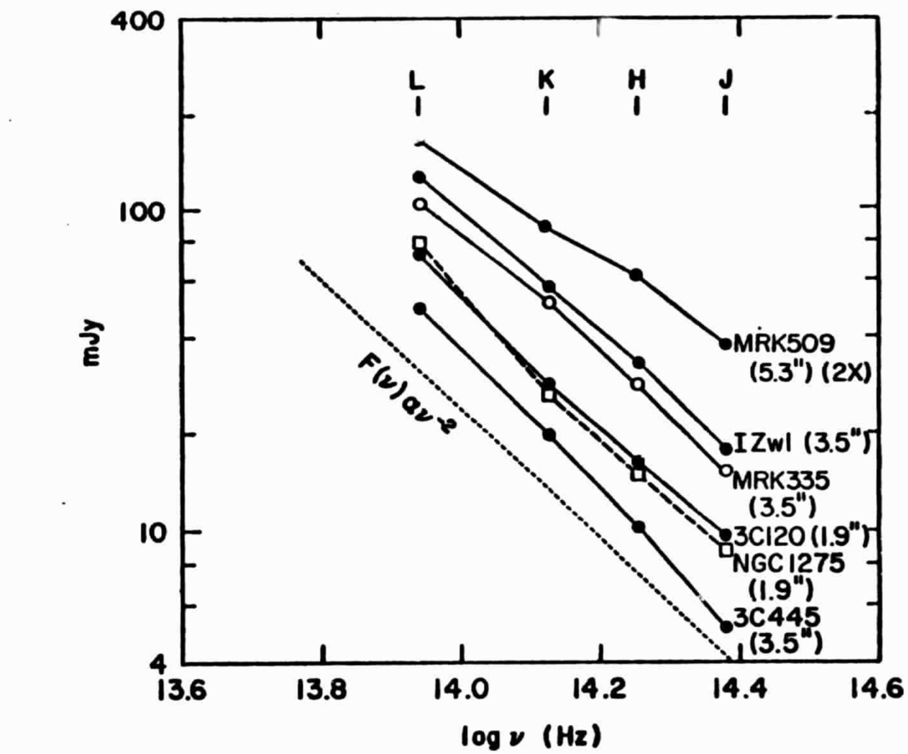
mJy
400
100
10
4
L
K
H
J
MRK509 (5.3") (2X)
IZwI (3.5")
MRK335 (3.5")
3C120 (1.9")
NGC 1275 (1.9")
3C445 (3.5")
$F(\nu)\alpha\nu^{-2}$
log ν (Hz)
13.6
13.8
14.0
14.2
14.4
14.6

Fig. 2