INFRARED OBSERVATIONS OF RADIO GALAXIES

George H. Rieke
University of Arizona
Tucson, Arizona 85719

I. INTRODUCTION

For technical reasons, infrared studies of active galaxies have lagged far behind optical and radio ones. This is unfortunate, since entirely new aspects of these sources are often revealed in the infrared. The extreme efficiency of dust at degrading ultraviolet photons into cool thermal emission frequently makes the luminosity of an extragalactic source inaccessible to optical and radio astronomers. At the same time, the effects of dust on optical emission line ratios and continuum shapes can be profound. The complete identification of samples of radio sources will require infrared observations to supplement the optical techniques now generally employed, and the extreme properties of the sources bright in the infrared can provide new insights to conditions in extragalactic nonthermal sources. To illustrate these points, I will discuss three cases: 1.) galaxies undergoing a powerful burst of star formation, 2.) intermediate type Seyfert galaxies, and 3.) an extreme infrared identification of an extragalactic radio source.

II. STARBURSTS

Early observations of the nuclei of apparently normal spiral galaxies revealed unexpectedly large excesses at 10 and 20µm (Kleinmann and Low 1970), suggesting that the luminosities of these regions were substantially underestimated in optical studies. This suggestion has been confirmed in more systematic infrared surveys (Rieke and Lebofsky 1978) and by extending the wavelength coverage into the far infrared, where the bulk of the luminosity is emitted (Telesco and Harper 1980; Harper, private communication).

There are a variety of indications that the observed luminosities are thermally reradiated by dust heated by hot stars produced in recent bursts of rapid star formation. Absorption and emission features associated with interstellar dust are prominent in the infrared spectra

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(Willner, Soifer, and Russell 1977; Lebofsky and Rieke 1979). The infrared sources have an extent of a few hundreds of parsecs (e.g., Rieke and Low 1975; Rieke 1976; Becklin et al. 1980; Rieke et al. 1980; Telesco 1981; Telesco and Gatley 1981), similar to the size of the complex of enormous HII regions around our Galactic Center. In some cases, the infrared emission originates in a ring of HII regions centered on the galactic nucleus (Telesco 1980; Telesco and Gatley 1981), strengthening the analogy with the Galactic Center. There are indications of a correlation of infrared luminosity with the mass in interstellar clouds (Rickard, Harvey, and Thronson 1980). There is a correlation of infrared luminosity with nonthermal radio luminosity (van der Kruit 1971; Rieke 1978), as might be expected if the radio emission is produced in supernova explosions of the young massive stars.

A quantitative test of the starburst hypothesis requires a comprehensive set of radio, infrared, and optical observations. Where such data are available, it has been possible to construct consistent models that account for the radio, infrared, optical, and x-ray properties of the galaxy, within the limitations of our current knowledge of the evolution of stars and of supernova remnants. These models are most complete for NGC 253 and M82 (Rieke et al. 1980). If current estimates of the masses of these galactic nuclei are correct, the models require that a very large percentage of the available interstellar material be converted into massive stars, with a corresponding suppression of the formation of solar-mass stars; star formation in these regions must proceed substantially differently from how it does in the solar neighborhood.

Despite the plausibility of these models, there has been little direct evidence for starbursts. Direct detection of the predicted population of luminous stars has been frustrated in the optical by extinction and in the infrared by technical difficulties. Recently, we (Lebofsky and Rieke, in preparation) have obtained improved infrared spectra of M82 and other starburst galaxies which show increased strength of the 12CO and 13CO stellar absorption bands near 2.4μm, as would be expected if a significant proportion of the near infrared fluxes from these galaxies is produced by supergiants. This observation provides a direct confirmation of the starburst hypothesis and should allow a more accurate study of the star formation process in galactic nuclei.

III. DUST IN SEYFERT GALAXIES

It is generally agreed that dust influences the properties of type 2 Seyfert galaxies by heavily reddening their emission lines and continua and by shifting the bulk of their luminosity into the infrared. As a result, it may be difficult to study the underlying luminosity sources in these objects. There is even a possibility that some starburst galaxies have been mis-classified as type 2 Seyferts. For example, both NGC 253 and M82 have very bright compact nuclei (obscured toward our direction because both galaxies are nearly edge-on); they both produce luminosities of the same order as typical type 2 Seyferts; and their emission lines show that the gas clouds around their nuclei undergo substantial noncircular motions. Viewed from a distance of 20 Mpc and more nearly face-on, it might be difficult indeed to distinguish these galaxies from type 2 Seyfert galaxies.

Spectroscopic observers, particularly Osterbrock and co-workers, have called attention to intermediate-type Seyfert galaxies with permitted emission lines that have narrow cores and broad wings. As shown by their violent optical variability, many of these objects are powered by compact nonthermal sources in their nuclei. However, coordinated photometry, polarimetry, and spectroscopy of NGC 4151, the prototype of these sources, indicates that its output between 1 and 3μm is dominated by reradiation by hot dust near its nucleus, and the emission between 3 and 100μm arises from cool dust in the region producing the narrow emission line components (Rieke and Lebofsky 1981). The cool dust significantly reddens the emission lines and probably also the nonthermal continuum. The amount of cool dust required in this model is not unreasonably large. In fact, it is consistent with the general observation that below ∿ 900 K, about 1% of the mass in interstellar gas will condense into dust, where the mass in gas is estimated from recombination theory and the strength of the narrow hydrogen line components. Therefore, comparable effects due to reddening and reradiation should be found in other intermediate type Seyfert galaxies.

The cool dust might be detected through 1.) a steep rise of the infrared continuum from 2 to 10μm; 2.) reddening of the hydrogen recombination lines; and 3.) reddening of the optical continuum.

To apply the first of these tests, I have supplemented the data of Rieke (1978) with that of McAlary, McLaren, and Crabtree (1979) to estimate the steepness of the infrared continuum for 23 type 1 or intermediate type Seyfert galaxies. The identification of intermediate type galaxies is very dependent on the resolution and signal to noise of the optical spectrophotometry; within this sample, Osterbrock (1977) identified Mrk 6, 79, 315 and NGC 3227, 4151, and 5548 as intermediate. A higher resolution spectrum of NGC 7469 (Heckman et al. 1981) shows it also to have narrow line cores. IC 4329A, not observed by Osterbrock, appears to have narrow line components (Wilson and Penston 1979; Pastoriza 1979). I have excluded Mrk 231 becaause of its many peculiarities. So far as is known, the other members of the sample are pure type 1s. The average infrared slope, $-\alpha$, for the intermediate type galaxies is 1.57 ± 0.17 and for the type 1s is 0.88 ± 0.08. The errors here are the standard deviation of the mean of the slopes. Thus, the average slope for the intermediate types is more than three standard deviations steeper than for the type 1s. In fact, with the exception of NGC 5548 (type 1.5) and Mrk 279 (type 1), all of the intermediate type galaxies have slopes steeper than any of the type 1s.

To apply the second test, I excluded Mrk 231 because of its peculiarities and IC 4329A because its edge-on aspect will produce additional extinction not associated with the nucleus. I also excluded the type 1.8 and 1.9 Seyferts (Osterbrock 1981), in case their exceedingly steep Balmer decrements have some origin other than reddening. The remaining intermediate type galaxies with available spectrophotometry (primarily by Osterbrock 1977 and Koski 1978) have an average $\langle H\gamma / H\beta \rangle = 0.33 \pm 0.022$, while the type 1s have $\langle H\gamma / H\beta \rangle = 0.44 \pm 0.026$. The intermediate galaxies have steeper decrements by more than 3 standard deviations

To apply the third test, Mrk 231 and IC 4329A were again excluded. It was assumed that U-B and B-V give an estimate of the slope of the optical continuum; the photoelectric photometry was taken from the compilatiion of Weedman (1977). The average B-V and U-B for the intermediate types were 0.695 ± 0.053 and -0.41 ± 0.084 respectively; for the type 1s they were 0.53 ± 0.042 and -0.63 ± 0.044. Each color is more than two standard deviations redder for the intermediate types.

Therefore, all three tests suggest that there is significant reddening in intermediate type Seyfert galaxies. In fact, the correlations between infrared slope and Balmer decrement and continuum slope that led me to conclude that dust plays an important role in type 1 Seyfert galaxies (Rieke 1978) existed from the inclusion of the intermediate type galaxies in the sample.

To explore this hypothesis more quantitatively, I have applied the model developed for NGC 4151 (Rieke and Lebofsky 1981) to a number of intermediate type galaxies. If $M_d / M_g = g$, and the parameters for NGC 4151 are unprimed while those for the other galaxy are primed, equation (1) of Rieke and Lebofsky (1981) yields

$$g'/g = (S'/S)\ (d\ I\ \theta^3 / d'\ I'\ \theta'^3\ ),^{.5} \qquad (1)$$

where S is the flux at the peak of the thermally reradiated spectrum, d is the distance to the galaxy, I is the intensity of the narrow component of H β, and θ is the angular diameter of the reradiating region. However, θ is proportional to $S^{.5}$, and we assume that d is proportional to redshift, z. Therefore,

$$g'/g = (S\ z\ I / S'\ z'\ I')^{.5} \qquad (2)$$

Table 1 shows the estimated values of g' for intermediate type galaxies. With the exception of Mrk 372, the calculated values all lie near the expected value of 1%. The steep Balmer decrements for this galaxy and also for Mrk 6, 315, and NGC 3227 indicate significantly stronger reddening than for NGC 4151. If the estimates of I/I' are corrected for the additional reddening in these cases, the final estimates of M_d/M_g are obtained. In all cases, the value is in satisfactory agreement with 1%.

Therefore, it seems likely that dust plays a very important role in intermediate type Seyfert galaxies. Whether the effects of dust are entirely sufficient to account for the extreme properties of type 1.8 and 1.9 galaxies, however, needs additional investigation since these sources are relatively little studied in the infrared.

Table 1

Name	type	S/S'	z/z'	I/I'	g'	M_d/M_g
Mrk. 6	1.5	9	0.19	1.6	0.01	0.003
79	1.2	8	0.15	10	0.02	0.02
315	1.5	20	0.083	26	0.04	0.02
372	1.8	100	0.11	67	0.16	0.05
NGC3227	1.2	5	1.0	16	0.05	0.03
4151	1.5	1.00	1.00	1.00	0.006	0.006
5548	1.5	7	0.20	7	0.02	0.02
7469	1.2	2.3	0.20	3.5	0.008	0.008

The pure type 1 galaxies require relatively little gas in their narrow line regions to produce the observed forbidden emission lines, thus accounting for the lack of cool dust. However, a very small amount of hot dust within or near their broad line regions would still dominate their outputs in the near infrared (in the case of NGC 4151, $\sim$ 0.1 $M_\odot$ of hot dust was sufficient). Since the infrared frequently contributes only a small fraction of the total luminosity of these sources, the expected degree of reddening can be small. This model can be tested by accurate measurements of the shape of the optical-infrared spectrum during variations. For example, observations of III Zw 2 suggest that its infrared excess component cuts off steeply near 1 μm as would be expected if it arose through thermal reradiation by hot dust (Lebofsky and Rieke 1980).

IV. NONTHERMAL SOURCES

Not all extragalactic infrared sources radiate thermally! A particularly interesting class of nonthermal source is the objects with very steep infrared spectra that are found at the positions of exceptionally faint optical identifications of radio sources (Rieke, Lebofsky, and Kinman 1979). These sources are discriminated against in optical surveys because so little of their total luminosity emerges in the visible or blue (Rieke and Lebofsky 1980). A number of the sources have power law slopes as steep as ν^{-3}. The state-of-the-art limit for source detections at 2μm is about magnitude 19. A source of this brightness and with a power law slope of -3 would be 23rd magnitude at 9000 Å and 25th at 6000 Å. Thus, given current technology, the completest possible identifications of extragalactic source samples will require infrared observations.

These steep spectrum sources provide unique opportunities to study the processes producing the optical-IR emission of QSOs. Some of these possibilities have been explored by Bregman et al. (1981) for the source 1413+135. They found this source to be strongly variable, highly polarized, and free of emission lines, therefore establishing a close relation to BL Lac-type objects. The source lies within a distant galaxy ($z = 0.26$); because of the steepness of the nonthermal spectrum, the galaxy can be studied in the optical without worry about contamination from its luminous nonthermal nucleus.

The above-mentioned characteristics indicate that the optical-infrared flux is produced by synchrotron radiation in a very compact region. The steep synchrotron spectrum does not connect smoothly to the x-ray flux; together with the compactness of the source deduced from its variability, this characteristic implies that a second mechanism, Compton scattering, produces the x-ray flux. Application of conventional synchrotron-self-Compton models to the source then indicates that it has a large magnetic field ($\sim$ 10 gauss) and exhibits bulk relativistic motion toward the observer (Bregman et al. 1981).

The steepening of the spectrum near 5μm approaches the maximum abruptness that can be achieved by a synchrotron-emitting source. The relativistic electron spectrum must terminate sharply at a maximum energy corresponding to a Lorentz factor of $\sim$300, and the magnetic field must be highly uniform in the emitting region. This extreme behavior is not unique to this source; early in its outburst in 1975, AO 0235+164 also exhibited a strongly curved spectrum with a dramatic increase in slope near 3μm and a cut-off toward shorter wavelengths nearly as sharp as is theoretically possible for synchrotron emission (Rieke et al. 1976).

If the source parameters derived for 1413+135 are typical of BL Lac type objects, a number of additional conclusions can be reached. For example, some of these objects show rotation of the polarization position angle between the optical and infrared (Rieke et al. 1977). A possible explanation was Faraday rotation in the relativistic plasma. However, with allowance for the dependence of relativistic electron density on magnetic field strength, it can be shown from the discussion of Pacholczyk (1974) that the degree of rotation goes inversely as the magnetic field strength to the power $(\gamma - 1)/2$ if the index in the power law energetic electron spectrum is γ. Thus, the large magnetic field strength in 1413+135 indicates that Faraday rotation will play a negligible role. An alternate possibility is that the position angle rotation arises when outbursts of relativistic electrons are directed into regions of differing magnetic field orientation (Impey, Brand, and Tapia 1981; Moore et al. 1981). Further support for this hypothesis is that the sources where rotation has been observed (AO 0235+164, 0735+178, OI 090.4, BL Lac; Impey, Brand, and Tapia, 1981; Rieke et al. 1977; unpublished observations) have exceptionally strong position angle variability (see, e.g., Angel and Stockman 1980), and relatively strong intensity variability. In addition, the spectra of these sources are frequently variable during outbursts (Rieke et al. 1976; O'dell et al.

1978). Thus, the wavelength dependence of polarization can arise in a natural way when a new injection of electrons with a different energy spectrum and polarization position angle adds its contribution to the pre-existing spectrum of the source.

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