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HIGH-RESOLUTION EMISSION-LINE IMAGING OF SEYFERT GALAXIES. II. EVIDENCE FOR ANISOTROPIC IONIZING RADIATION

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ABSTRACT

In the preceding paper, we describe a direct imaging survey of Seyfert galaxies with "linear" radio structures and find that the major axes and spatial scales of the circumnuclear emission-line gas are very similar to those of the radio continuum sources. In the present paper, the nature of this close connection between thermal and relativistic gases is assessed in detail. Models in which the kinetic energy of the radio jets or plasmoids powers shock waves, which ionize the gas, seem energetically feasible but disagree with the off-nuclear line intensity ratios. Ionization by relativistic electrons is negligible, but they may contribute to the heating of the gas. We favor a scenario in which the radio jets and plasmoids shock, accelerate, and compress ambient and entrained gas, but the dominant source of ionization is the nonstellar nuclear ultraviolet continuum. This ultraviolet source appears to be partially beamed along the axis of the radio jet. Photoionization by ultraviolet synchrotron radiation generated via shocks in the ejecta may also contribute, especially in Seyfert 2 galaxies.

A comparison between the number of ionizing photons, N_i, inferred by extrapolation of the directly observed continuum, and the number of ionizing photons, $N_{\mathrm{H}\beta}$, required to generate the Hβ emission has been made for six galaxies in our sample. In at least two galaxies, we find $N_i \ll N_{\mathrm{H}\beta}$, suggesting that the gas is exposed to a higher ionizing flux than inferred from direct observations of the nucleus, and supporting the idea of partial beaming. Similarly, the energy in the continuum between 100 Å and 1 μm, if emitted isotropically, is inadequate to fuel the thermal nuclear infrared sources, implying that the radiating dust is heated by a more luminous optical-ultraviolet source. We speculate that the nuclear infrared emission of Seyfert 2 galaxies arises from dust in molecular clouds exposed to the partially beamed radiation, and we predict that the 10 μm sources should align with the radio axes. The partial beaming of the optical-ultraviolet radiation may arise through "shadowing" by a dense, obscuring torus, or it could reflect the intrinsic distribution of photons radiated by the accretion disk as a function of angular distance from its rotation axis ("polar diagram").

Subject headings: galaxies: jets — galaxies: Seyfert — galaxies: structure — radio sources: general

I. INTRODUCTION

In the preceding paper (Haniff, Wilson, and Ward 1988, hereafter Paper I), a direct imaging survey of 11 Seyfert galaxies in the Hα and [O III] $\lambda\lambda$4959, 5007 emission lines is reported. The galaxies observed were chosen to contain "linear" radio sources (i.e., double, triple, or "jetlike" radio sources, straddling the optical continuum nucleus). However, the classification of the radio structure of one of them (NGC 5135) as "linear" is very doubtful, so we omit it from further discussion. The results of the survey of the remaining 10 may be summarized as follows:

1. The [O III] $\lambda\lambda$4959, 5007 emission-line region is spatially resolved in all the galaxies. The amount of information in the emission-line distributions ranges from slight in galaxies with very compact ($\lesssim 0\farcs8$) radio doubles and emission-line regions (e.g., NGC 591 and NGC 4051) to detailed in galaxies with very extended narrow line regions (e.g., Mrk 78 and Mrk 573). In addition, Hα is spatially extended in almost all the galaxies.

2. After smoothing VLA radio maps to the optical seeing, a comparison between emission-line and radio continuum distributions was possible. The position angles of the major axes of the [O III] and radio continuum images generally agree to within the errors of measurement (see col. [7], Table 2 of Paper I). These errors are large when the radio/emission-line region is compact, and in such cases (e.g., NGC 591) only an alignment in the same quadrant can be demonstrated. In most galaxies, however, the agreement of radio and emission-line axes is excellent, typically to better than ±5°, which is within the measurement errors. There is also good agreement between radio and Hα axes (col. [8], Table 2 of Paper I). Such alignment between the linear radio source and the high-excitation narrow-line region is now established in about 15 Seyfert galaxies (see Wilson 1987 for other examples).

3. The spatial extents of the radio doubles/triples and the bright inner regions of emission-line gas are very similar. The degree to which a comparison can be made depends, as above, on the angular extent. For compact regions, Gaussian deconvolutions from the effects of seeing and the radio beam show similar radio and emission-line FWHM (e.g., NGC 4051). For extended cases, detailed correspondences between the mor-

phologies are found. In Mrk 78, much of the [O III] emission is associated with the outer radio clouds. The distribution of [O III] appears to be double, straddling the optical continuum peak, and associated with the radio components in Mrk 34 and perhaps in Mrk 1066. The [O III] distribution in Mrk 573 shows a bright central core plus extended emission at the locations of the outer radio components. Association between high-excitation gas and radio lobes appears, therefore, to be a common property of Seyfert galaxies.

4. Examination of columns (9) and (10) of Table 2 in Paper I shows a possible tendency for the major axes of the optical *continuum* isophotes and the radio source to align when the position angle of the continuum isophotes refers to the *same spatial scale* as the radio source. The degree of alignment is, however, by no means as good as that between the radio and emission-line gases.

Section II is devoted to a discussion of the nature of the relationship between the radio continuum and optical emission-line distributions. This effect clearly indicates a close connection between the synchrotron-emitting relativistic particles and magnetic fields, and the thermal gas at $\sim 10^4$ K which is responsible for the emission lines. We discuss various possible physical processes which could be responsible and use arguments based on observational and simple energetic criteria to constrain them. In § III, we present comparisons between the number of ionizing photons inferred from the observed continua and the number inferred from the Balmer line fluxes, and also between the powers in the continuum available to heat dust and the thermal, nuclear infrared luminosities of the Seyfert 2's in our sample. The results tend to favor the idea that the optical-ultraviolet continua are not radiated isotropically. Conclusions are summarized in § IV.

II. NATURE OF THE RELATIONSHIP BETWEEN THE RADIO CONTINUUM AND EMISSION-LINE GASES

The connection between the relativistic and thermal gases could arise because either: (*a*) the kinetic energy of the ejected radio-emitting clouds is responsible for the heating and/or ionization of the line emitting gas; or (*b*) the thermal gas is ionized and/or heated by relativistic particles, the presence of which is indicated by the radio synchrotron radiation; or (*c*) the ejected radio plasma compresses ambient or entrained thermal gas, increasing the emissivity of the lines and rendering them more readily visible in the vicinity of the radio components than elsewhere, independent of the details of the heating and ionization; or (*d*) ionizing photons escape preferentially along the rotation axis of the disk which is presumed to collimate the radio ejecta, or one which is coplanar with it.

We discuss these possibilities in turn.

a) Kinetic Energy Models

A correlation between the monochromatic radio power at 1.4 GHz and the [O III] $\lambda5007$ luminosity has been noted by a number of workers (de Bruyn and Wilson 1978; Phillips, Charles, and Baldwin 1983; Whittle 1985). Figure 1 is a related diagram in which the ratio of the integrated radio luminosity [*L*(radio)] to the total emission-line luminosity of the narrow-line region [*L*(narrow lines)] is plotted against *L*(narrow lines). The radio luminosity has been found by integrating the radio spectrum from 10 MHz to 100 GHz. The spectrum was taken to be of power-law form, $S \propto \nu^{-\alpha}$, with index α determined from flux density measurements at two or more centimetric wavelengths, if available. We used $\alpha = 0.75$ if the galaxy has been detected at only one radio wavelength. For most galaxies plotted in Figure 1, detailed spectrophotometric observations are not available. By using the model calculations of optical and ultraviolet line intensities by Ferland and Osterbrock (1986), supplemented by Koski's (1978) measurements of lines not included in their Table 5, we estimate that the total power in line emission from the narrow line region is *L*(narrow lines) ≈ 14 *L*([O III] $\lambda5007$) on average. This relationship has been used to derive all the line luminosities plotted in Figure 1, which contains all Seyfert galaxies with measurements of both [O III] $\lambda5007$ and radio continuum fluxes. No corrections for obscuration were applied to the [O III] $\lambda5007$ fluxes. As may be seen from Figure 1, the ratio *L*(radio)/*L*(narrow lines) ranges between 10^{-2} and 10^{-4} for *L*(narrow lines) in the range 10^{40}–10^{44} ergs s^{-1}. Allowance for obscuration would make the ratio even smaller.

If both the radio continuum and emission lines are powered solely by the kinetic energy of the same outflow, we may write

$$L(\text{radio}) = \epsilon_r\, L(\text{kinetic})\,,$$

and

$$L(\text{narrow lines}) = \epsilon_1\, L(\text{kinetic})\,,$$

where ϵ_r and ϵ_1 are the efficiencies with which kinetic energy is converted into nonthermal radio and optical plus ultraviolet emission lines, respectively. From the data plotted in Figure 1, we have $\epsilon_r/\epsilon_1 \approx 10^{-4}$–$10^{-2}$.

Generation of line emission in such a model would occur via thermalization of the outflow in shocks, with the value of ϵ_1 depending on the shock properties. The power per unit area converted into heat in a strong shock is of order $\rho_{\text{no}} V_s^3/2$, where ρ_{no} is the preshock mass density and V_s is the shock velocity. An estimate of the emission efficiency is then $\epsilon_1 \approx 2I(\text{narrow lines})/\rho_{\text{no}} V_s^3$, where *I*(narrow lines) is the sum of the intensities of the narrow lines per unit area of shock. Unfortunately, the appropriate values for ρ_{no} and V_s in the present context are unknown, and are likely to vary from galaxy to galaxy. As an illustration, we consider the emission-line spectra of plane radiative shocks with velocities in the range 40–200 km s^{-1}, typical preshock densities of 10 cm^3 and preshock magnetic fields of 1 μG, which have been calculated by Shull and McKee (1979) and Raymond (1979). For our purposes, such a range of parameters could apply to shocks driven into interstellar clouds by a lower density, high-velocity outflow, such as a radio jet or an expanding lobe. By summing the intensities of the optical and ultraviolet lines calculated by Shull and McKee (1979, their Tables 7 and 8), and adding estimates of the intensities of a few lines they did not include, ϵ_1 may be obtained. We find $\epsilon_1 \approx 0.2$–0.4. Thus a scenario in which the line emission originates in such shocks and the radio emission is also powered by the flow would be *energetically* consistent with the data, if *L*(kinetic) $\gtrsim 10^{40}$–10^{44} ergs s^{-1} (see Fig. 1), $\epsilon_1 \approx 0.2$–0.4 and $\epsilon_r \approx (10^{-4}$–$10^{-2})\epsilon_1$. Shocks with much lower or much higher velocities would have smaller ϵ_1. A more extensive discussion is precluded by our ignorance of the shock parameters and the limited range of shock models currently available.

A serious difficulty for all shock models, however, concerns the ratios of the emission-line intensities. It has long been known that the (narrow) emission-line ratios in spatially unresolved spectra of Seyfert galaxies are indicative of photoionization by a power-law spectrum (e.g., Koski 1978; Ferland and Shields 1985). More recently, spatially resolved, low-dispersion

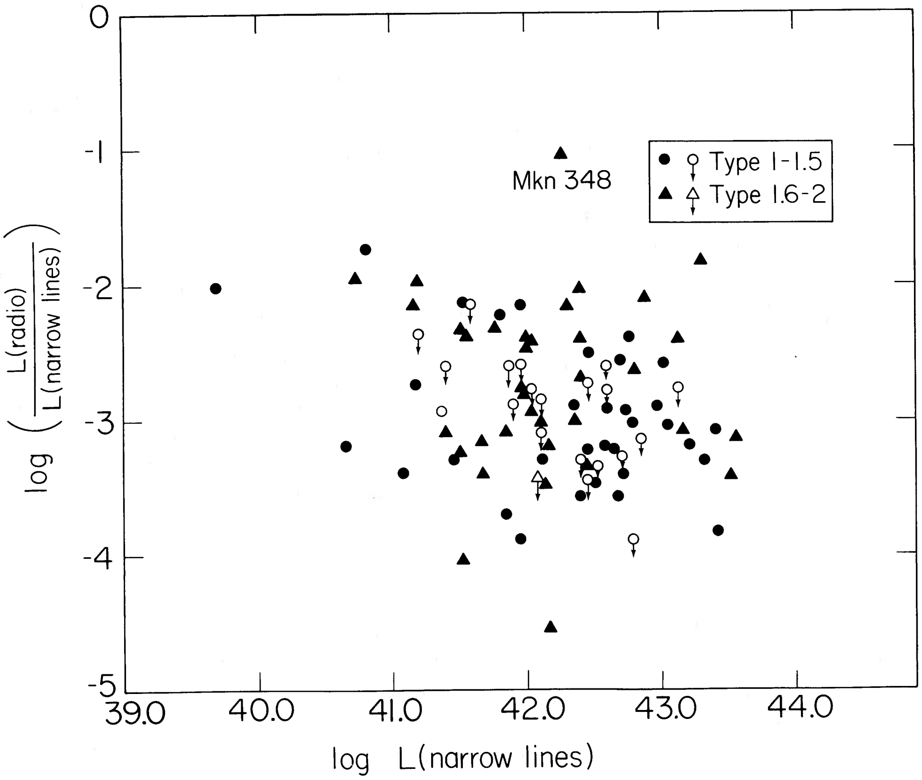

FIG. 1.—Plot of the ratio of the total radio luminosity, *L*(radio), to the total emission-line luminosity of the narrow-line region, *L*(narrow lines), against *L*(narrow lines). All Seyfert galaxies with measurements of both [O III] λ5007 and radio continuum fluxes are plotted. Seyfert types 1–1.5 and 1.6–2 are plotted with different symbols. Open symbols represent upper limits. The radio luminosities were calculated from radio fluxes and spectral indices in de Bruyn and Wilson (1976), Wilson and Meurs (1982), Condon *et al.* (1982), Ulvestad and Wilson (1984*a*, *b*), Morris *et al.* (1985), Ulvestad (1986), Schommer *et al.* (1987), and Ulvestad and Wilson (1988). The emission-line luminosities were obtained as described in the text, using measurements of the flux of [O III] λ5007 in Adams and Weedman (1975), Koski (1978), MacAlpine, Williams, and Lewis (1979), Yee (1980), Hawley and Phillips (1980), Osterbrock (1981), Shuder and Osterbrock (1981), Phillips and Malin (1982), Phillips, Charles, and Baldwin (1983), Goodrich and Osterbrock (1983), Ulvestad and Wilson (1983), and Penston *et al.* (1984).

spectra of a few galaxies with linear radio sources have been obtained (Balick and Heckman 1979; Wilson, Baldwin, and Ulvestad 1985), showing that the off-nuclear emission-line spectra are also characteristic of power-law photoionization. Whittle *et al.* (1988) have published medium-high dispersion long-slit spectra of the Hβ, [O III] λλ4959, 5007 region for 10 Seyferts with linear radio structures. They find that in the approximately seven cases where line-emitting components can be associated with the radio lobes, the flux ratios *F*([O III] λ5007)/*F*(Hβ) ≈ 10–15 for these components, which is very similar to the corresponding values for the nuclear components. These ratios are typical of power-law photoionized nebulae, and much higher than expected in steady flow, radiative shock wave models, even when shock velocities comparable to the emission line widths are considered (see Binette, Dopita, and Tuohy 1985 for models with shock velocities in the range 100–1000 km s^{-1}). It is noteworthy, however, that some finite age/optically thin shock models do exhibit *F*([O III] λ5007)/*F*(Hβ) ratios comparable to those observed (Binette, Dopita, and Tuohy 1985). Low-dispersion data including other lines (especially [O II] λ3727) can distinguish such models from the power-law photoionized case.

Currently available data, then, favor the notion that the emission-line gas associated with the radio components is photoionized by a power-law continuum source. Such a source could either be located in the nucleus (see § II*d* below) or be associated with the radio lobes themselves. In the context of kinetic energy models, the latter situation could arise if cosmic-ray electrons are accelerated *in situ*, presumably via shock waves in the flow, to energies capable of radiating ultraviolet synchrotron emission: $\gamma = E/mc^2 \approx 10^6$–$10^7$ for magnetic fields of $\sim 10^{-4}$ G. There is currently no evidence for such spatially extended, nonthermal sources of ionizing photons in Seyferts, but such a picture cannot be ruled out and might be attractive for Seyfert 2's, where the evidence for an ultracompact ionizing source is weaker than in Seyfert 1's. Searches with the Hubble Space Telescope for extended ultraviolet synchrotron sources in Seyfert galaxies would be very valuable. We emphasize that the above difficulties with the line ratios in "pure" shock wave models do not preclude scenarios in which the high-velocity gas in the narrow-line region is *accelerated* by the action of jets (Wilson 1982) or expanding radio lobes (Pedlar, Dyson, and Unger 1985; Wilson and Ulvestad 1987) on entrained or ambient interstellar gas. Shock waves are almost certainly present in and around the radio components and models including *both* their effects and those of photoionizing sources are clearly relevant (see Contini and Aldrovandi 1983).

b) Ionization and/or Heating by Relativistic Particles

The effects of heating and ionization by relativistic particles on the emission-line spectra of active galactic nuclei have been considered recently by Ferland and Mushotzky (1984), Cesar, Aldrovandi, and Gruenwald (1985), and Gruenwald and Viegas-Aldrovandi (1987). By making a number of simplifying assumptions, Ferland and Mushotzky calculated the ratio of the rates of the relativistic electron (ξ) to photoelectric (Q) heat inputs as well as the ratio of the ionization rate by relativistic particles (Γ^*) to the ionization rate by conventional photoionization. Writing $P_{\rm rel}$ and $P_{\rm th}$ for the relativistic electron and thermal pressures, respectively, U for the ionization parameter [$U = Q(H)/4\pi N_e r^2 c$, with N_e the thermal electron density and r the separation between the ionizing source and the cloud in question), and β for the ratio of total heating by the cosmic rays to Coulomb heating (β takes into account collective effects; e.g., Scott *et al.* 1980], Ferland and Mushotzky's (1984) equations (9) and (10) may be written

$$\frac{\xi}{Q} = \frac{0.04\beta P_{\rm rel}}{P_{\rm th}} ,$$

and

$$\frac{\Gamma^*}{\Gamma} = \frac{10^{-8}}{U} \frac{P_{\rm rel}}{P_{\rm th}} .$$

Here a temperature of 10^4 K has been adopted for the thermal gas. Photoionization models of the narrow-line region generally require an ionization parameter $U \approx 10^{-2}$ to reproduce the line ratios (e.g., Ferland 1981). If the relativistic electron and thermal pressures are comparable, as commonly appears to be the case in Seyferts (de Bruyn and Wilson 1978; Pedlar, Dyson, and Unger 1985; Unger *et al.* 1986), it is clear that the ionization rate by relativistic electrons is negligible in comparison with that by photons, as also concluded by Ulvestad (1981).

The relativistic electrons could be a significant source of heating, especially if collective effects are important. Ferland and Mushotzky (1984) studied the effect of the cosmic rays on the line ratios in a model of the narrow-line region with density $N = 10^3$ cm^{-3} and $U = 10^{-2}$. They found that the cosmic rays first affect the emission-line spectrum when $\beta P_{\rm rel} \approx 10^{-9}$ ergs cm^{-3}, comparable to the thermal pressure. Therefore the detailed emission-line spectrum will be influenced by the presence of the cosmic rays, but they are probably not the dominant factor in defining the morphological correspondence between the radio and emission-line gases. As Ferland and Mushotzky (1984) note, there remain many theoretical uncertainties, such as the effect of the magnetic field in impeding the motion of cosmic rays into and through the emission-line clouds, the magnitude of collective effects and the densities of relativistic and subrelativistic protons, which cannot be inferred from the radio synchrotron spectrum. Further calculations of the effects of relativistic electrons on a photoionized gas would be valuable.

c) Compression of Thermal Gas by the Radio Ejecta

In its "purest" form, this scenario would attribute the alignment of the [O III] emission with the radio axis solely to *compression* of gas by the radio ejecta (and consequent enhancement of emission-line emissivity), even when the central ($\lesssim 1$ pc) photoionizing source radiates *isotropically*. As discussed above, the compression would presumably occur through the agency of radiative shock waves driven into entrained or ambient thermal material. Weak line emission would be expected from gas photoionized by the supposed isotropic nuclear source in directions away from the radio axis. This picture accounts naturally for the identical *spatial scales* of the radio lobes and the high-velocity gas, but as there is now considerable evidence for anisotropic escape of ionizing photons from the inner nucleus (see below), we suspect that this mechanism is not wholly responsible for the observed relation between the radio and emission-line gases.

d) Anisotropic Escape of Ionizing Photons

In this picture, the emission-line gas is photoionized by a compact (≤ 1 pc) nuclear source, but the ionizing photons escape preferentially along the axis of the disk which also collimates the radio jet (e.g., Osterbrock 1983). We summarize here the evidence in favor of this point of view.

1. As noted above, off-nuclear optical spectroscopy often shows line ratios similar to the nuclear ones and characteristic of gas photoionized by a power law. Examples of such high ionization emission-line regions associated with linear radio sources in Seyfert galaxies include NGC 1068 (Balick and Heckman 1979; Baldwin, Wilson, and Whittle 1987), NGC 2110 (Wilson, Baldwin, and Ulvestad 1985), NGC 5643 (Morris *et al.* 1985), and NGC 5929 (Whittle *et al.* 1986).

2. In some cases, the nuclear nonstellar ultraviolet source, as estimated by extrapolation of the observed optical or ultraviolet continuum, apparently fails to provide enough ionizing photons to account for the recombination line emission. In NGC 1068, Baldwin, Wilson, and Whittle (1987) found this discrepancy to be a factor of at least 20, and perhaps as high as 200, for an off-nuclear cloud of high ionization gas apparently photoionized by the nucleus, while for gas in the nucleus itself, Neugebauer *et al.* (1980) claimed a factor of 6 discrepancy. A similar effect is probably present in NGC 2110 (Wilson, Baldwin, and Ulvestad 1985). Such discrepancies suggest the presence of sources of ionizing radiation which are invisible from Earth (perhaps because of obscuration) but which do shine out in some directions and illuminate the emission-line clouds (Neugebauer *et al.* 1980). One particular geometry involves the radiation escaping preferentially along the disk rotation axis, so the clouds in this direction are exposed to a much brighter ionizing flux than inferred via direct observations of the continuum from Earth. It is unclear whether this anisotropic photon escape, if it occurs, is an intrinsic property of the ionizing source, or whether it results from greater dust obscuration in the plane of the disk than along its rotation axis. The ionizing spectrum "seen" by an emission-line cloud a long way from a thin accretion disk is a function of the angular distance of the cloud from the disk's rotation axis (Netzer 1987), but it is doubtful whether the required degree of "collimation" can be produced in this way. The evidence that this possible deficit of ionizing photons in relation to the recombination line radiation is a common property of Seyfert 2 galaxies is discussed in depth in § III.

3. While NGC 1068 is traditionally classified as a Seyfert 2 galaxy, Antonucci and Miller (1985) have found that its optical polarized flux spectrum resembles the flux spectrum of a Seyfert 1 galaxy, with broad Balmer lines of FWZI $\approx$ 7500 km s^{-1}. They interpret their observations in terms of a torus of obscuring material surrounding the broad-line region and compact continuum source; these components can thus not be observed directly from Earth. The polarized continuum and broad emission lines result from the presence of a high-latitude gas of scattering particles, probably warm electrons, which partially scatter these radiations into our line of sight. The axis

of the torus required by the polarization observations is close to the direction of the radio jet.

4. Long-slit, high-dispersion spectra, oriented both along and perpendicular to the radio axes of a number of Seyfert galaxies, including some of those imaged in the present paper, have recently been obtained by Unger *et al.* (1987). These workers find high-excitation, very weak, narrow emission lines extending much further along the radio axis than perpendicular to it. Since the faint emission lines extend out well beyond the observed radio components, the kinetic energy and relativistic particles associated with the radio jets and lobes apparently play no role in ionizing or heating this gas. The gas is apparently normally rotating disk gas which has been photoionized by the nuclear source.

e) Summary

In summary, we feel that the gas associated with the radio lobes is almost certainly photoionized by a power-law, or similar, continuum source. This ultraviolet source could be located either *in situ*—i.e., within or near the lobes—or, more likely, in the compact ($\lesssim 1$ pc) nucleus iteself. In the latter case, there is compelling evidence that the source does not emit isotropically, but is partially beamed along the radio axis. Such partial beaming can explain the alignment of radio and emission-line axes, but not the close agreement between the spatial *extents* of the radio and high-velocity thermal gas. An additional effect must be present, most likely compression of entrained or ambient thermal gas by the radio ejecta. The jet or expanding lobes drive radiative shocks into the gas, forming cool dense condensations, which are maintained in an ionized state by the ultraviolet source. It is possible, but less likely, that relativistic particles also contribute to the heating of the gas. High resolution emission-line imaging with the Hubble Space Telescope should define in finer detail the relationship between relativistic and thermal gases in Seyfert galaxies.

If the ultraviolet source is partially beamed along the radio axis, we expect that the number of ionizing photons estimated from the recombination line emission will, in most cases, be larger than that inferred directly from extrapolation of the observed optical-ultraviolet continuum. For the same reason there may also be discrepancies between the thermal infrared output and the observationally inferred number of optical-ultraviolet photons capable of heating dust to the required temperatures. In the next section we attempt a quantitative exploration of these questions for type 2 Seyfert galaxies.

III. IS THERE AN “ENERGY DEFICIT” IN SEYFERT 2 GALAXIES?

a) The Ionizing Continuum and the Recombination Line Emission

The method of estimating the number of ionizing continuum photons available and comparing this with the number required to produce the hydrogen line emission is, in principle, straightforward. Assuming radiative recombination under case B conditions, the relevant formulae are

$$N_{\mathrm{H}\beta} = 2.1 \times 10^{52}(L_{\mathrm{H}\beta}/10^{40} \text{ ergs s}^{-1}) \text{ photons s}^{-1} ,$$

where $N_{\mathrm{H}\beta}$ is the number of ionizing photons necessary to produce an Hβ luminosity $L_{\mathrm{H}\beta}$, and

$$N_i = 4\pi D^2 C(\alpha h)^{-1}(\nu_1^{-\alpha} - \nu_2^{-\alpha}) .$$

Here N_i is the number of photons in the continuum between ν_1 and ν_2, D is the distance to the source, C is the constant in the flux density spectrum $F = C\nu^{-\alpha}$, and h is Planck's constant. We take $\nu_1 = 3.3 \times 10^{15}$ Hz (912 Å) and $\nu_2 = 4.8 \times 10^{17}$ Hz (2 keV), noting that for the range of spectral indices considered here, N_i is insensitive to the exact choice of ν_2.

In practice a number of problems arise in estimation of the relevant parameters, which introduce uncertainties into the comparison of $N_{\mathrm{H}\beta}$ and N_i:

1. Most of the ionizing photons are not directly observable. We shall assume a power-law form for the continuum, based on observations at optical, ultraviolet, and X-ray wavelengths. If Seyfert 2's were to have “big blue bumps,” like those inferred for some Seyfert 1's and quasars, this method could result in a considerable underestimate of the number of ionizing photons.

2. The corrections for absorption and reddening are uncertain. In fact, these parameters need to be known along three different paths: (1) our line of sight to the ionizing continuum source, (2) our line of sight to the line-emitting gas, and (3) the path between the ionizing continuum source and the line-emitting gas. Estimates of (1) and (2) will be made from published observations, on a galaxy by galaxy basis. In the ultraviolet, we shall use the reddening law given by Code *et al.* (1976). We adopt $A_v = 0$ for path (3), since our philosophy is to make assumptions which *minimize* any apparent excess of $N_{\mathrm{H}\beta}$ over N_i. If $A_v > 0$ for (3), the number of ionizing photons incident on the emission-line clouds will be reduced, thereby increasing any discrepancy.

3. Optical observations of the supposedly nonthermal continuum may be contaminated by stellar radiation. This problem is particularly pertinent to the few cases in which the nonthermal continuum is known in only the optical band.

4. The covering fraction of the ionized gas, as seen from the continuum source, is not known. A novel feature of our analysis is use of the emission-line images, when appropriate, to place upper limits on the covering fraction. These limits are again taken conservatively, with the philosophy of minimizing any calculated excess of $N_{\mathrm{H}\beta}$ over N_i. Further, calculations indicate that the volume of gas needed to emit a certain power in a given line is much smaller than the overall volume occupied by the gas. The line-emitting gas is thus concentrated in condensations or cloudlets, with a small filling factor, and probably intercepts only a small fraction of the ionizing continuum. The magnitude of this covering factor is unknown and, in accord with our conservative approach, we have not included it in the calculations. Allowing for a small covering factor, due to the gas being confined to cloudlets, would greatly amplify any calculated excess of $N_{\mathrm{H}\beta}$ over N_i.

We have restricted our calculations to the Seyfert 2 galaxies for which observations were described in Paper I, plus NGC 1068. In addition, we required at least two of the following four observational parameters to be known: the nonstellar optical flux at some wavelength, the slope of the optical nonstellar continuum, an ultraviolet flux, and a soft X-ray flux. Because of a lack of such information, Mrk 1066, NGC 591, and NGC 5135 are omitted from the discussion. Our results for the other galaxies are summarized in Table 1.

Markarian 3.—Malkan and Oke (1983) derived reddenings of $E_{B-V} = 0.27$ mag for the emission lines and $E_{B-V} = 0.50$ mag for the nuclear continuum of this galaxy. We have, therefore, performed the comparison between $N_{\mathrm{H}\beta}$ and N_i for both $A_v = 0.8$ mag and 1.5 mag. The flux of the nonstellar optical continuum at 5500 Å, its spectral index α, and the Hβ flux were also taken from Malkan and Oke (1983). These authors also

TABLE 1

THE NUMBER OF IONIZING PHOTONS INFERRED FROM THE CONTINUA AND THE NUMBER REQUIRED TO PRODUCE THE Hβ EMISSION LINES[a]

Galaxy	α	log C	log N_i	log $N_{H\beta}$	A_v(mag)	$N_{H\beta}/N_i$	Method for Power Law
Mrk 3	1.30	−6.84	52.62	53.76	0.8(1 & c)	14	Optical slope
	1.00	−10.83	53.40	54.09	1.5(1 & c)	5	Optical slope
	1.00	−10.83	53.40	53.76	0.8(1) 1.5(c)	2.3	Optical slope
Mrk 34	1.51	−3.78	<53.42	53.59	0(1 & c)	>1.5	Opt. point plus X-ray limit
	1.51	−3.78	<53.42	54.10	1.1(1) 0(c)	>5	Opt. point plus X-ray limit
Mrk 78	1.77	0.13	52.08(E) 51.81(W)	52.91(E) 52.66(W)	0(1 & c)	6(E) 7(W)	Ultraviolet spectrum
	1.77	0.13	52.08(E) 51.81(W)	53.39(E) 53.15(W)	1.05(1) 0(c)	20(E) 22(W)	Ultraviolet spectrum
	1.16	−8.05	53.54(E) 53.27(W)	53.39(E) 53.15(W)	1.05(1 & c)	0.7(E) 0.8(W)	Ultraviolet spectrum
Mrk 270	1.54	−3.43	<51.90	51.86	0(1 & c)	>0.9	Opt. point plus X-ray limit
	1.54	−3.43	<51.90	52.23	0.8(1) 0(c)	>2	Opt. point plus X-ray limit
Mrk 573	1.12	−10.17	52.32	52.62	0(1 & c)	2.0	Extrapolation optical plus X-ray point
	1.0	−11.08	53.32	53.08	1.0(1 & c)	0.6	Extrapolation optical plus X-ray point
NGC 1068	1.10	−8.39	52.91	52.89	0.3(1 & c)	1.0	Optical slope
	0.90	−10.94	53.55	53.16	0.9(1 & c)	0.4	Optical slope
	1.55	−1.64	52.71	52.74	0(1 & c)	1.1	Ultraviolet spectrum

[a] Columns give the galaxy name, the spectral index, α, and normalization, C, of the continuum ($F_\nu = C\nu^{-\alpha}$), the number of ionizing photons available in the continuum, N_i, the number of ionizing photons required to produce the observed Hβ flux, $N_{H\beta}$, the ratio $N_{H\beta}/N_i$, the visual absorption assumed, A_v, followed in parenthesis by 1 if the value of A_v was applied to Hβ and by c if it was applied to the continuum, and the method used to define the continuum power law (see text). All values of N_i, except those for Mrk 78 (see text), assume a 100% covering factor by the ionized gas.

obtained a continuum spectrum with *IUE*, but the data are too noisy to provide a useful constraint on the spectrum.

Using a covering factor of 100% and the lower value of the reddening for both line and continuum, we find there are too few ionizing photons to produce the appropriately dereddened Hβ luminosity by more than a factor of 10 (Table 1). When the power law used in this calculation is extrapolated to 2 keV, it predicts a flux that is somewhat higher than the X-ray measurement, but within a factor of 2 of it. Using the same assumptions and the higher value of the reddening, the deficiency of ionizing photons is reduced to a factor of ~ 5. The extrapolation of the power law to 2 keV in this case predicts a flux too high by a factor of 40. If, following Malkan and Oke (1983), we adopt $A_v = 0.8$ mag for the lines and $A_v = 1.5$ mag for the nonstellar continuum, the discrepancy is only a factor of ~ 2.

In view of the elongated form of the [O III] nebulosity and its alignment with the radio axis, we may assume a covering factor for the narrow-line region of $\lesssim 100\%$, but a precise value is hard to obtain (cf. Fig. 1 of Paper I). Conservatively speaking $\lesssim 50\%$ seems reasonable which would increase all the above numbers by a factor of 2. While all the numbers are subject to considerable uncertainty, there does seem to be some discrepancy between the extrapolated, observed continuum and the number of ionizing photons required to power Hβ in Mrk 3. This conclusion would be firm if the line emission has the same morphology as the radio source (Fig. 1*e* of Paper I).

Markarian 34.—Considerably less information is available for this galaxy than for Mrk 3. For the continuum, we have used an estimate of the optical nonstellar continuum together with an upper limit to the X-ray flux, both from Kriss, Canizares, and Ricker (1980). This procedure estimates the maximum number of ionizing photons if the entire optical to X-ray spectrum is a power law and its reddening zero. The Hβ flux has been taken from Koski (1978), whose measurements were generally made through a 2″.7 × 4″ aperture. If emission-line gas extends over a larger area, the value of $N_{H\beta}$ will be underestimated, and any excess of $N_{H\beta}$ over N_i reduced. For the case of no reddening, there are $\sim 50\%$ too few ionizing photons, an insignificant difference. If the Hβ flux (but not the continuum) is dereddened using the observed Balmer decrement (Koski 1978), with an assumed intrinsically case B decrement, the discrepancy is a factor of ~ 5. As for Mrk 3, the linear, possibly double, narrow-line region certainly reduces the covering factor below 100%, perhaps to $\lesssim 40\%$ (see Fig. 3*c* of Paper I), or to $\sim 5\%$ if the emission-line gas is concentrated in the radio lobes (Fig. 3*e* of Paper I). While this effect tends to increase the above small discrepancies, a definite conclusion cannot be drawn in the absence of information on the ultraviolet spectrum and its reddening.

Markarian 78.—For this object, we extrapolate the *IUE* spectrum to estimate the number of ionizing photons. The continuum fluxes at 2500 Å (Ferland and Osterbrock 1986) and at 1450 Å (Wu, Boggess, and Gull 1983) imply $\alpha = 1.77$ and log $N_i = 53.04$. Extrapolation of this spectrum to 2 keV gives an X-ray flux within a factor of 2 of that observed (Kriss, Canizares, and Ricker 1980). Using the [O III] image, we estimate that the emission-line regions to the east and west of the nucleus subtend $\sim 11\%$ and 6%, respectively, of all sky at the nucleus. These covering factors are upper limits and will be smaller if either the line-emitting gas is actually in condensations with a small filling factor (see above) or the gas is concentrated within the off-nuclear radio components (Fig. 4*e* of Paper I). If the ionizing continuum source is compact, located at the optical continuum peak and radiates isotropically, we obtain the values of N_i available for the east and west components separately (Table 1). The short time scale variability in the soft X-rays from Mrk 78 (Urry *et al.* 1986) provides support for our assumption that the ultraviolet source is compact. Taking the total Hβ flux given by Koski (1978) and assuming a uniform [O III] λ5007/Hβ ratio (Whittle *et al.* 1988), the values of $N_{\mathrm{H}\beta}$ can be calculated separately for the two components (Table 1). Comparison of N_i and $N_{\mathrm{H}\beta}$ then indicates a deficit in the number of ionizing photons available by a factor of ~ 7 for both east and west components.

The above calculations assume $A_v = 0$ for both the line and continuum fluxes. Ferland and Osterbrock (1986) deduced $A_v = 1.05$ mag for the emission lines. If this correction is applied to Hβ but not to the continuum, the discrepancies become 20 (east component) and 22 (west component); see Table 1. Ferland and Osterbrock (1986) considered that the ultraviolet continuum of Mrk 78 suffers little reddening, so the data strongly favor these last discrepancies. As an illustration, however, we consider the consequences of assuming that the *IUE* continuum is reddened by the same amount as the emission lines and then extrapolate it to determine N_i. In this case, there are sufficient ionizing photons (Table 1). However, such a continuum is most improbable, for an extrapolation predicts ~ 230 times the X-ray flux observed at 2 keV. We conclude that the model with A_v(lines) = 1.05 mag and $A_v(\mathrm{cont}) \approx 0$ is the most plausible, so that the deficit between the number of ionizing photons needed to power the Hβ line and the number available from the continuum is a factor of ~ 20. We reemphasize that this conclusion results from the assumptions that the ultraviolet source is compact, associated with the optical nucleus and radiates isotropically.

Markarian 270.—The data on this galaxy are quite limited, so we follow the same procedure as for Mrk 34. The continuum is defined by the nonstellar flux at 4400 Å and the upper limit to the X-ray flux at 2 keV (Kriss, Canizares, and Ricker 1980). The Hβ flux is taken from Koski (1978). For zero reddening, N_i and $N_{\mathrm{H}\beta}$ are essentially equal. If the reddening inferred from the Balmer line decrement is applied to Hβ, but not to the continuum, the discrepancy is a factor of 2 (Table 1). This difference is insignificant in view of our ignorance about the ultraviolet continuum of Mrk 270.

Markarian 573.—The sources for the Hβ line strength are Koski (1978) and Ulvestad and Wilson (1983), and we have averaged their measurements. Koski has also estimated the nonstellar fraction of light in the continuum at the wavelength of Hβ. This continuum has been extrapolated by Ferland and Osterbrock (1986) to derive a flux at 2500 Å. Joining this last flux to the soft X-ray point (Ulvestad and Wilson 1983) with a power-law spectrum, and making no reddening correction, we find that there are about half the ionizing photons required to account for the Hβ luminosity (Table 1). As an illustration of the effects of reddening, we have dereddened the Hβ and 2500 Å continuum fluxes by $A_v = 1.0$ mag (as implied by the Balmer decrement; Koski 1978) and extrapolated the continuum to shorter wavelengths, arbitrarily assuming $\alpha = 1.0$. The result is that the ionizing continuum contains 1.7 times as many photons as required to power Hβ (Table 1). However, this continuum may be too bright, since its extrapolation to soft X-rays gives a flux 18 times too high. Thus, the lack of ultraviolet continuum information precludes a conclusion if the covering factor is 100%. The [O III] image is highly elongated (Fig. 7*a* of Paper I), suggesting a small covering factor, although a substantial part of the flux is contained in an unresolved source coincident with the nucleus.

NGC 1068.—This galaxy is not included in our imaging sample, but we make the photon balance calculation because detailed observations are available, and to serve as a comparison. We follow Malkan and Oke (1983) and consider two possible continuum forms. The first is appropriate to $A_v = 0.3$ and has $\alpha = 1.1$, and the second to $A_v = 0.9$ with $\alpha = 0.9$. Once again, the consistency of such continua can be checked by extrapolation to the X-ray region [$F_x(2\ \mathrm{keV}) \approx 4.8 \times 10^{-30}$ ergs cm^{-2} s^{-1} Hz^{-1}; Monier and Halpern 1987]. For the first continuum form (lower reddening), near equality between N_i and $N_{\mathrm{H}\beta}$ (Hβ flux from Koski 1978) is found (Table 1). However, the extrapolation to 2 keV provides ~ 30 times the observed flux. For the second continuum form (higher reddening), $N_i = 2.5\ N_{\mathrm{H}\beta}$ (Table 1), but the extrapolation to 2 keV provides ~ 300 times the observed flux. These spectra are almost certainly too flat, and, as an alternative, we use the ultraviolet spectrum favored by Monier and Halpern (1987), which has $\alpha = 1.55$. This spectrum gives $N_i \approx N_{\mathrm{H}\beta}$ and its extrapolation to 2 keV agrees with the observed flux to within a factor of 2. Our conclusion is that for a 100% covering factor of the ionized gas, there is no discrepancy between N_i and $N_{\mathrm{H}\beta}$ for the nuclear source in NGC 1068. The difference between this conclusion and that of Neugebauer *et al.* (1980) is indicative of the uncertainty in the intrinsic spectrum of the ionizing photons.

The circumnuclear, high-velocity line-emitting gas in NGC 1068 lines up with the radio source (Walker 1968; Wilson and Ulvestad 1982; Cecil, Tully, and Bland 1986), so a covering factor $\leqslant 100\%$ is likely. Also, the gas is likely to be clumped. Further, Baldwin, Wilson, and Whittle (1987) have shown that for a region of high-ionization gas some 20″ from the nucleus along the radio axis, there are too few nuclear ionizing photons (by a factor of 20–200), if the ultraviolet radiation is radiated isotropically. These arguments favor partial beaming of the ultraviolet radiation along the radio axis.

b) The Dust-Heating Continuum and the Thermal Infrared Emission

Dust absorbs energy efficiently between ~ 100 Å and 1 μm and emits between 1 and 100 μm (Carleton *et al.* 1987). A natural model for the nuclear infrared emission of Seyfert 2's is one in which dust grains are heated by radiation in the former band and reradiated in the latter. In principle, a straightforward comparison between the powers available in the two bands can check whether the dust "sees" the same 100 Å–1 μm continuum as we infer from direct observation. If the inferred power (L_{H}) in the 100 Å–1 μm band is equal to or greater than the 1–100 μm power (L_{IR}), a model in which both bands are emitted isotropically would be consistent with the data. On the other hand, if there is a deficiency of dust heating in comparison with dust radiated power, we must infer that either there are extra sources of 100 Å–1 μm radiation which heat the dust but are hidden from our view, or that the 100 Å–1 μm radiation is not emitted isotropically. A special case of the former situation would be a single, totally obscured, dust-heating source. In view of the evidence (§ III*a*) for partial beaming of the ionizing radiation, it seems worthwhile to explore whether the same may be true of the band which heats the dust.

In practice, two complications arise. First, the *IRAS* fluxes reflect the sum of the emission from the nucleus and the galaxy. Second, there is potentially a direct contribution to the infrared emission from the low-frequency extension of the optical–ultraviolet power law. We restrict our discussion to four of the six galaxies discussed in § III*a*: Mrk 3, Mrk 78, Mrk 573, and

NGC 1068. The other two, Mrk 34 and Mrk 270, do not have sufficient multifrequency data available to justify detailed calculations.

There are both qualitative and quantitative ways of estimating the ratio of nuclear to nonnuclear infrared emission. All the objects discussed here have *warm IRAS* colors, with the energy distribution (log νf_ν vs. log ν), peaking around log $\nu \approx 13$ ($\lambda \approx 30$ μm). This suggests that the infrared emission is dominated by nuclear activity rather than cooler normal bulge or disk emission. Quantitatively, we can compare the ground-based small-aperture measurements at 10 and 20 μm with the much larger aperture *IRAS* measurements at 12 and 25 μm. For Mrk 3, we find that about half the total emission at 10 and 20 μm originates from inside $8\farcs5$. This ratio need not be the same for the flux at 60 and 100 μm, but since the peak occurs at 30 μm, a correction of a factor 2 would be appropriate to estimate the nuclear component of the *IRAS* fluxes. For NGC 1068, there is a similar difference between the *IRAS* 12 and 25 μm measurements and those at 10 and 20 μm through an $8\farcs5$ ground-based aperture. Indeed, Telesco *et al.* (1984) have shown that half of the total infrared luminosity from NGC 1068 is associated with the Seyfert nucleus and half with the starburst disk. We have, therefore, estimated the nuclear infrared luminosity ($L_{\rm IR}$) for all four galaxies by dividing the total infrared luminosity by a factor of 2.

For Mrk 3, Mrk 573, and NGC 1068, the contribution of the optical-ultraviolet power law (Table 1) to the infrared luminosity is negligible. For Mrk 78, the low-frequency extension of the ultraviolet power law appropriate to $A_v = 0$ could dominate the infrared light if it extended to 30 μm. However, this is clearly not the case, since the *IRAS* spectrum of this galaxy is dominated by a strong peak near 30 μm, which is totally inconsistent with significant emission from the power law. Any direct contribution of the optical-ultraviolet power law to the infrared emission has, therefore, been neglected in all four objects.

The results are summarized in Table 2, where $L_{\rm H}$ has been obtained by integrating the continua given in Table 1 for the specified value of A_v from 100 Å to 1 μm. The only case with $L_{\rm H} > L_{\rm IR}$ is Mrk 78, when $A_v = 1.05$ mag is assumed. As discussed in § III*a*, this value of A_v is actually derived from the emission lines, and it is most unlikely that the ultraviolet continuum of Mrk 78 is reddened by this amount (Ferland and Osterbrock 1986). In all other cases, $L_{\rm H} < L_{\rm IR}$, the deficit ranging from a factor of 2.2 to 19. In general, these results tend to support a model in which the dust radiating the nuclear infrared emission is heated by a continuum with intrinsically more power than is inferred from direct observations of the nucleus. One particular model with these properties is one in which *the dust-heating continuum, like the ionizing continuum, is partially beamed along the radio axis.* We may envisage dense molecular clouds, lying along or near the radio axis, being exposed to this luminous heating source, and their warm dust dominating the nuclear infrared output. A prediction of this model is that the mid-infrared sources in Seyfert galaxies with linear radio sources should align with their radio axes. There is already evidence that this may be the case in NGC 1068. Tresch-Fienberg *et al.* (1987) have resolved the 10 μm nuclear source in this galaxy into two components, one associated with a weak radio peak in the jet and the other with the nucleus. These authors note several difficulties with the idea that the off-nuclear source originates from dust heated by the nuclear continuum. However, at least some of the problems may be overcome in our scenario, in which the continuum responsible for heating the dust is much more luminous than direct observations of the nucleus indicate. If this picture is correct, we expect the nuclear source as well will line up with the radio axis when adequate spatial resolution becomes available in the mid-infrared. This source might, for example, be connected with the $0\farcs7$ scale radio triple in NGC 1068 (Ulvestad, Neff, and Wilson 1987). Our view differs from that of Krolik and Begelman (1988), who ascribe the nuclear infrared emission to warm dust in the obscuring torus which was invoked by Antonucci and Miller (1985) to account for their polarization observations.

TABLE 2

THE INFRARED LUMINOSITY AND THE DUST-HEATING ENERGY AVAILABLE IN THE CONTINUUM[a]

Galaxy	A_v	log $L_{\rm IR}$	log $L_{\rm H}$	$L_{\rm IR}/L_{\rm H}$
Mrk 3	0.8	43.94	42.79	14
Mrk 3	1.5	43.94	43.41	3.4
Mrk 78	0	44.25	43.53	5.2
Mrk 78	1.05	44.25	44.59	0.46
Mrk 573	0	43.67	42.39	19
Mrk 573	1.0	43.67	43.33	2.2
NGC 1068	0	44.21	43.03	15
NGC 1068	0.3	44.21	43.14	12
NGC 1068	0.9	44.21	43.68	3.4

[a] Columns give the galaxy name, the assumed A_v (in magnitudes), the observed infrared luminosity, $L_{\rm IR}$, the power available to heat the dust, $L_{\rm H}$ (both in ergs s^{-1}), and the ratio $L_{\rm IR}/L_{\rm H}$. The spectrum assumed to calculate $L_{\rm H}$ is identified by the value of A_v and Table 1. All the observed values of $L_{\rm IR}$ have been reduced by a factor of 2 to set more realistic limits on the nuclear thermal component (see text).

IV. CONCLUSIONS

The principal conclusions of this paper and Paper I are as follows:

1. In Seyfert galaxies containing double, triple, or jetlike radio sources, there is an excellent correspondence between the major axes of the radio source and the high-velocity, emission-line gas (narrow line region).
2. The spatial extents of the relativistic and thermal gases are very similar, and typically of order several hundred parsecs. In at least three cases, there is strong evidence that the [O III] image has a double structure associated with the outer radio components.
3. Shock waves or relativistic particles are probably not the dominant source of ionization of the off-nuclear thermal gas. Rather, this gas is almost certainly photoionized by a continuum source with a power-law, or similar, spectrum.
4. The ultraviolet continuum source probably resides in the compact ($\lesssim 1$ pc) nucleus, but the ionizing radiation appears to be partially beamed along the radio axis. This last conclusion is favored by the morphology of the ionized gas and by an intercomparison of the number of ionizing photons calculated by extrapolation of the observed optical, ultraviolet, or X-ray continuum (N_i) and the number required to power the narrow-line Hβ emission by radiative recombination ($N_{{\rm H}\beta}$). We find $N_i \ll N_{{\rm H}\beta}$ in at least two type 2 Seyferts, suggesting that the gas is exposed to a higher intensity of ionizing continuum radiation than is observed along our line of sight to the nucleus. The solid angle of the cone into which the ionizing photons are

"beamed" would be expected to be wavelength-dependent if the anisotropy is an intrinsic property of the accretion disk. Direct, high-resolution images in different emission lines covering a range of ionization potential and critical density could be used, in conjunction with a photoionization model, to map out the variations of both the intensity of ionizing radiation and the thermal gas density as a function of distance along and from the cone's axis. Such work would provide very direct constraints on the properties of the central ionizing source. Ultraviolet photons generated *in situ* by synchrotron radiation within the jet are another potential source of ionization.

5. A comparison between the power in the optical–ultraviolet continuum available to heat dust (L_H) and the thermal luminosity of the nuclear infrared source (L_{IR}) shows $L_{IR}/L_H \approx 2$–20 in four type 2 Seyfert galaxies with linear radio structure. This result suggests that more radiation is available to heat the dust than escapes from the nucleus along our line of sight. As for the ionizing radiation, one possibility is preferential escape of part of the 100 Å–1 μm continuum along the radio axis. The nuclear infrared emission of Seyfert 2 galaxies would then arise from dust in molecular clouds heated by this beamed ultraviolet radiation. If so, the thermal 10 μm sources in Seyfert 2 galaxies should align with their radio axes. The well-known correlation between radio and infrared luminosities in Seyfert galaxies would then reflect a relation between the power in the jet and the power in the partially beamed ultraviolet light which heats the dust.

6. There is a possible broad trend (requiring further observations for confirmation) for the radio axes to align with the optical continuum axes on a similar spatial scale. This optical light could originate either in compact stellar barlike features or be direct synchrotron radiation from the radio jet or be scattered nuclear continuum light.

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