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CIRCUMNUCLEAR "STARBURSTS" IN SEYFERT GALAXIES

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ABSTRACT. Observational diagnostics for the recognition of circumnuclear star formation in Seyfert galaxies are described and illustrated. These methods include: a) spatially resolved optical spectroscopy, which allows the emission lines from HII regions to be separated from those originating in gas ionized by the Seyfert nucleus, b) radio continuum mapping, where the "linear" radio sources characteristic of the nuclear activity may be distinguished from the "diffuse" morphology of multiple supernova remnants generated in a starburst, c) infrared spectroscopic searches for emission features of dust, which are seen in starbursts but not in Seyfert nuclei, and d) the shape of the IRAS spectrum. These various diagnostics agree well as to the presence or absence of ongoing star formation. The IRAS spectra of a significant fraction of Seyferts are dominated by emission from dust heated by stars, not the Seyfert nucleus itself. In these cases, the spectrum is curved, being steep between 25 and 60μm and flatter between 60 and 100μm. When the Seyfert nucleus dominates, the 25-100μm spectrum is much flatter ($\alpha > -1$). It is suggested that the location of a Seyfert galaxy in the IRAS color-color diagram [$\alpha(60,25)$ vs $\alpha(100,60)$] reflects primarily the relative contributions of the active nucleus and dust heated by stars (circumnuclear or disk) to the infrared fluxes.

1. INTRODUCTION

The topic of star formation in active galaxies is of interest for two main reasons. First, it has been suggested that much of the far infrared emission observed by IRAS from Seyfert galaxies may result from an extended, non-nuclear component, perhaps dust heated by hot stars (e.g. Rodriguez-Espinosa, Rudy and Jones 1986). Much of the continuing controversy about the origin of luminous infrared emission focusses on the separation of nuclear and extended components, and on the emission mechanism of the nuclear component itself (thermal vs. non-thermal). Second, there are hints that the nuclear activity seen in objects like Seyfert galaxies and quasars may somehow be connected with enhanced star formation in the circumnuclear or galaxy-scale environment. No clear view of this possible relation exists, but discussions favoring it have fallen into one of two categories. In the first, the entire active nucleus phenomenon is attributed to star formation and its consequences (stellar winds, supernovae, supernova remnants, compact stellar remnants etc.). While few would argue that all the properties of Seyfert type 1 galaxies and quasars can be so explained, the idea that stars provide the ionizing radiation in Seyfert 2 galaxies has been widely discussed (e.g. Adams and Weedman 1975; Harwit and Pacini 1975). Pronik (1973) suggested that a mixture of the central stars of planetary nebulae and normal hot main sequence stars is the ionizing source, while Terlevich and Melnick (1985) have recently argued that the presence of massive stars with effective temperatures of more than 100,000 K (extreme Wolf-

Rayet stars) can result in emission line spectra which resemble Seyfert 2's or LINER's. Another, more speculative, suggestion is that starbursts may evolve into Seyfert galaxies if the compact stellar remnants resulting from the former settle into nuclear regions of radii ~ 1 pc, and then act as the accretors of a "conventional" active nucleus (Weedman 1983). In this view, a single massive black hole is not required, although the multiple accretors may mimic one in terms of many observational manifestations. In the second category of models, the active nucleus really does contain a "classical" supermassive black hole, but the black hole activity is triggered by, or triggers, a surrounding starburst. For example (see paper presented by C.A. Norman at this meeting), the starburst may facilitate dissipation of the angular momentum of interstellar gas, leading to enhanced accretion onto the black hole. Alternatively, the impact of high velocity nuclear ejecta, such as emission line clouds, winds or jets, on dense molecular gas could trigger a starburst.

As emphasised above, the properties of the putative nuclear starburst in the first category of models must be very different from those of "normal" star forming regions. Possible reasons include a high stellar and gaseous density in the nucleus which may, for example, lead to overlapping stellar winds and supernova remnants, and other unfamiliar phenomena. Yet in the outskirts of such a starburst, there must surely be relatively normal HII regions. Similarly, in the second category of models, when an evolutionary sequence from starburst to black hole activity (or vice versa) occurs, careful observations should reveal "composite" nuclei, unless the first form of activity completely disappears before the second one begins. Thus both categories of models predict an excess of circumnuclear star formation in comparison with non-active galaxies of similar morphological type, luminosity, etc. The key test of all of the above conjectures involves an observational check of this prediction.

In this paper, I should like to review a number of methods by which intense circumnuclear star formation may be diagnosed in Seyfert galaxies. The results of these different methods generally turn out to be in excellent agreement. In particular, I shall emphasize how the high spatial resolutions available at radio and optical wavelengths allow a clear separation of the effects of the nuclear activity proper from star formation going on around it.

2. MANIFESTATIONS OF STAR FORMATION IN SEYFERT GALAXIES

2.1 Optical Emission Line Studies

The ideal method of investigating the presence of hot young stars is to observe emission lines from their HII regions. A wide body of both low (e.g. Osterbrock 1977; Koski 1978) and high (e.g. Heckman et al. 1981; Whittle 1985) dispersion spectra exist on the nuclei of Seyfert galaxies. These data are unsuitable for detection of circumnuclear starbursts, because emissions from the HII regions are usually swamped by the Seyfert nucleus. Although Véron et al. (1981) were able to deduce the presence of HII regions in the nuclei of the Seyfert galaxies NGC 7496 and NGC 7582 by noting that Hβ is narrower than [OIII]λ5007, spatially resolved spectra are usually needed. Separation of the emission lines of the HII regions from those of gas ionized by the Seyfert nucleus can then be achieved in two ways. First, the line ratios, as determined through low dispersion optical spectra, are quite different in the two types of nebulosity (e.g. Baldwin, Phillips and Terlevich 1981). Second,

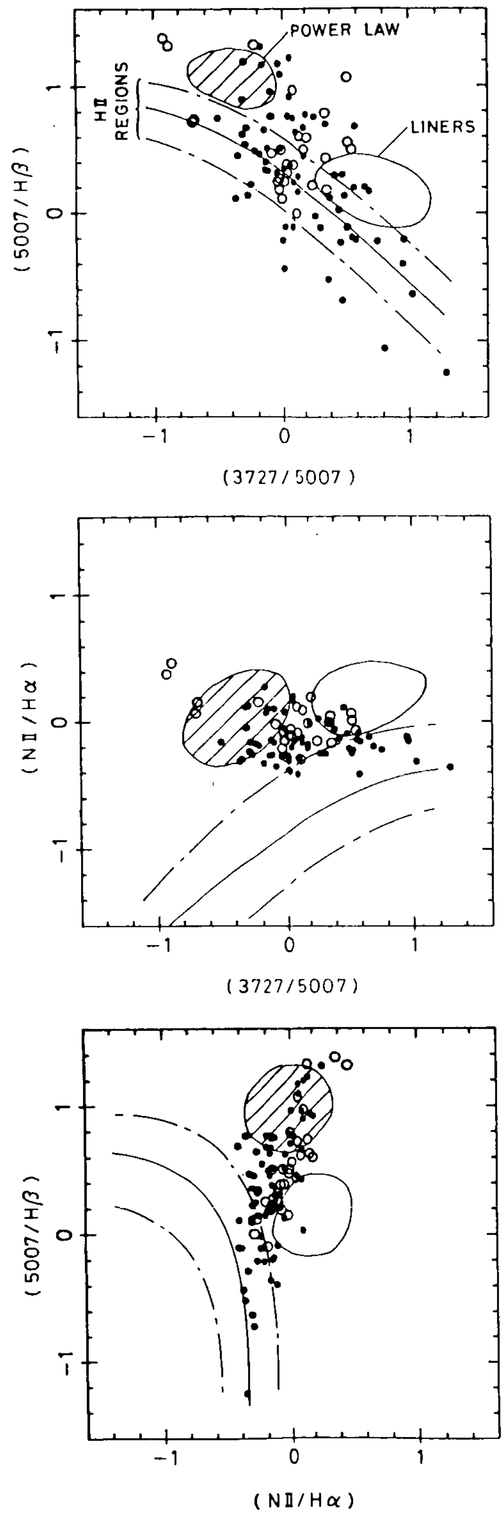

Figure 1 - Ionization diagrams showing logarithms of intensity ratios at different locations over NGC 1068, along with regions found by Baldwin, Phillips and Terlevich (1981) to be the domains of various ionization mechanisms. From Baldwin, Wilson and Whittle (1986).

the HII regions generally lie in a rotating disk or flattened distribution which is coplanar with the stellar disk further out, while the kinematics of the Seyfert excited gas ("narrow line region") are dominated by radial (inflow or outflow) motions (e.g. Heckman et al. 1981). In the following, I describe examples of the separation of Seyfert and starburst excited gas with each of these two methods.

2.1.1. Emission line Ratios. Recently, Baldwin, Wilson and Whittle (1986) have performed an extensive study of NGC 1068 by means of long slit spectra at about 30 locations over the face of the galaxy. The resulting ≃ 1500 spectra have been used to study the kinematics and ionization structure of the gas. Some of the results are illustrated in Fig. 1, which gives plots of ratios of emission lines ([OIII]λ5007/Hβ vs [OII]λ3727/[OIII]λ5007; [NII]λ6584/Hα vs [OII]λ3727/[OIII]λ5007; [OIII]λ5007/Hβ vs [NII]λ6584/Hα) which are useful for diagnosing the ionization mechanism. Each plotted point represents the line ratios at one location in the galaxy. The line ratios have been corrected for reddening assuming an intrinsic Hα/Hβ ratio of 2.86 (Brocklehurst 1971) and the reddening law of Whitford (1958). The regions of the diagrams occupied by normal HII regions, power law ionized gas and LINER's are indicated by the bands and oval shaped regions. As may be seen, the points range between the region occupied by HII regions and that which is characteristic of power law photoionized gas. Baldwin, Wilson and Whittle (1986) discuss the possibility that some of the gas is shock ionized, but prefer the idea that we are observing two components projected on top of each other. One gaseous component is ionized by the Seyfert nucleus and the other by hot stars in the starburst disk of NGC 1068; the exact location of a point in Fig. 1 then reflects the relative contributions of the two components along any given line of sight. There are other pieces of evidence supporting this view, including an early stellar population in the low excitation regions, differences in velocity field and line profiles between Hβ and [OIII]λ5007, and differences between the spatial distributions of the gases emitting these two lines.

2.1.2. Emission Line Kinematics. A recent investigation (Wilson et al. 1986) of the circumnuclear region of the type 1 Seyfert galaxy NGC 7469 illustrates the different kinematics of the nuclear starburst and the high excitation narrow line region. From long slit, high dispersion mapping of the emission lines Hβ, [OIII]λλ4959, 5007, Hα and [NII]λλ6548, 6584, we reached the following conclusions:

a) In addition to the spatially unresolved broad line region, two blended components of extended emission line gas are found. The first component is of high excitation ([OIII]λ5007/Hβ >> 1, [NII]λ6584/Hα ~ 1) and is presumably photoionized by the Seyfert nucleus, while the second is of low excitation and appears to arise in circumnuclear HII regions.

b) The high excitation component dominates the [OIII] lines, which are broad, show strong, blueward-slanting profile asymmetries and have a velocity field with a minimum near the nucleus. The kinematics of this component are thus dominated by radial motions. The low excitation component, as seen in Hα, Hβ and [NII] outside the immediate vicinity of the nucleus, emits much narrower lines and follows rotational motion in or parallel to the plane of the stellar disk of the galaxy. The difference between the line profiles of Hβ and [OIII]λ5007 may be seen in Figs. 2a and b, which shows their distribution over the circumnuclear region.

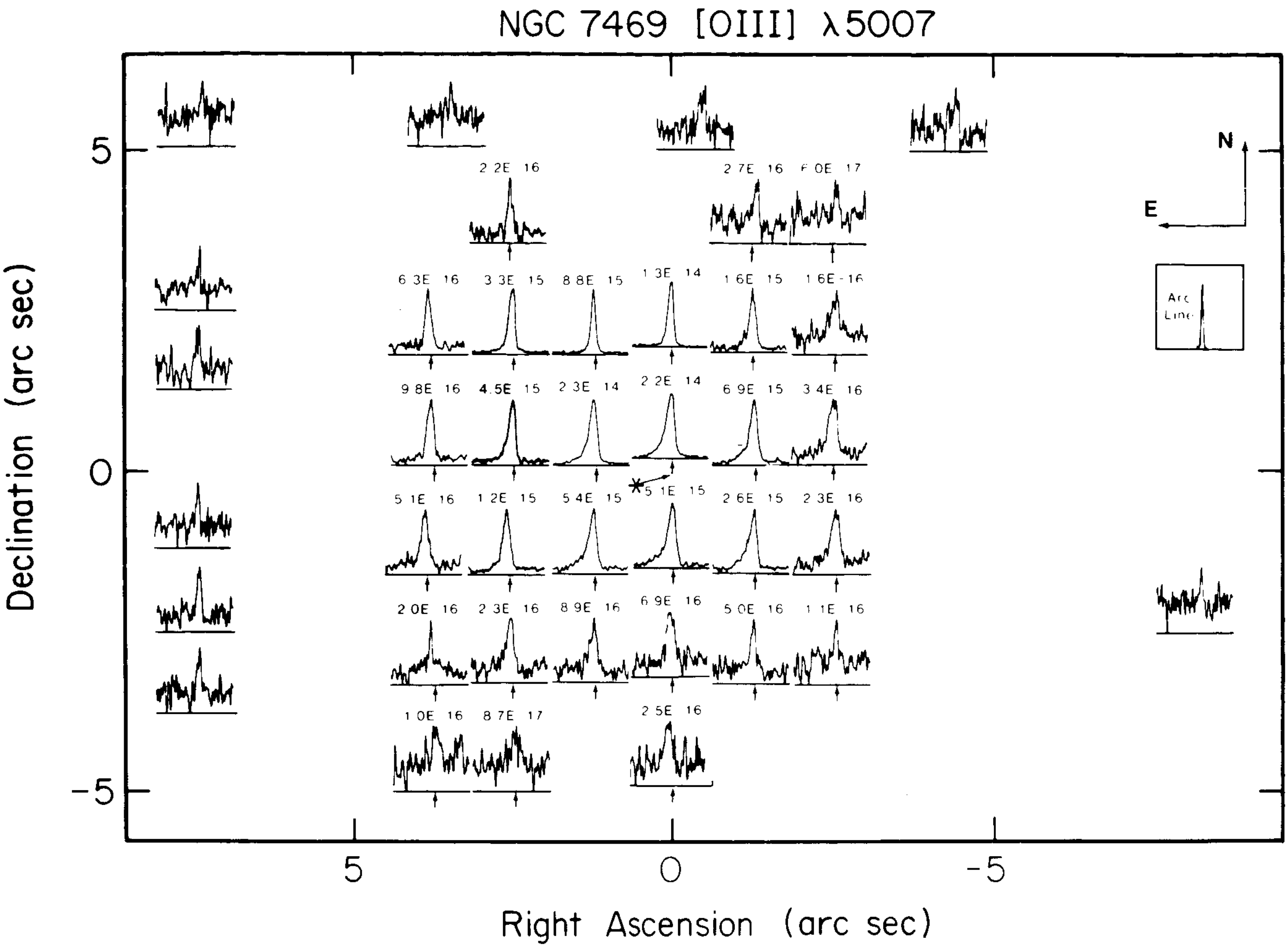

Figure 2a - Profiles of [OIII]λ5007 in NGC 7469. Each profile is normalized so that the difference between the maximum and minimum monochromatic fluxes over the range of wavelengths plotted is the same physical height. The total range of velocity plotted is 3400 km s^{-1}. The nominal position of the nucleus is indicated by the asterisk and the arc line shows the instrumental response.

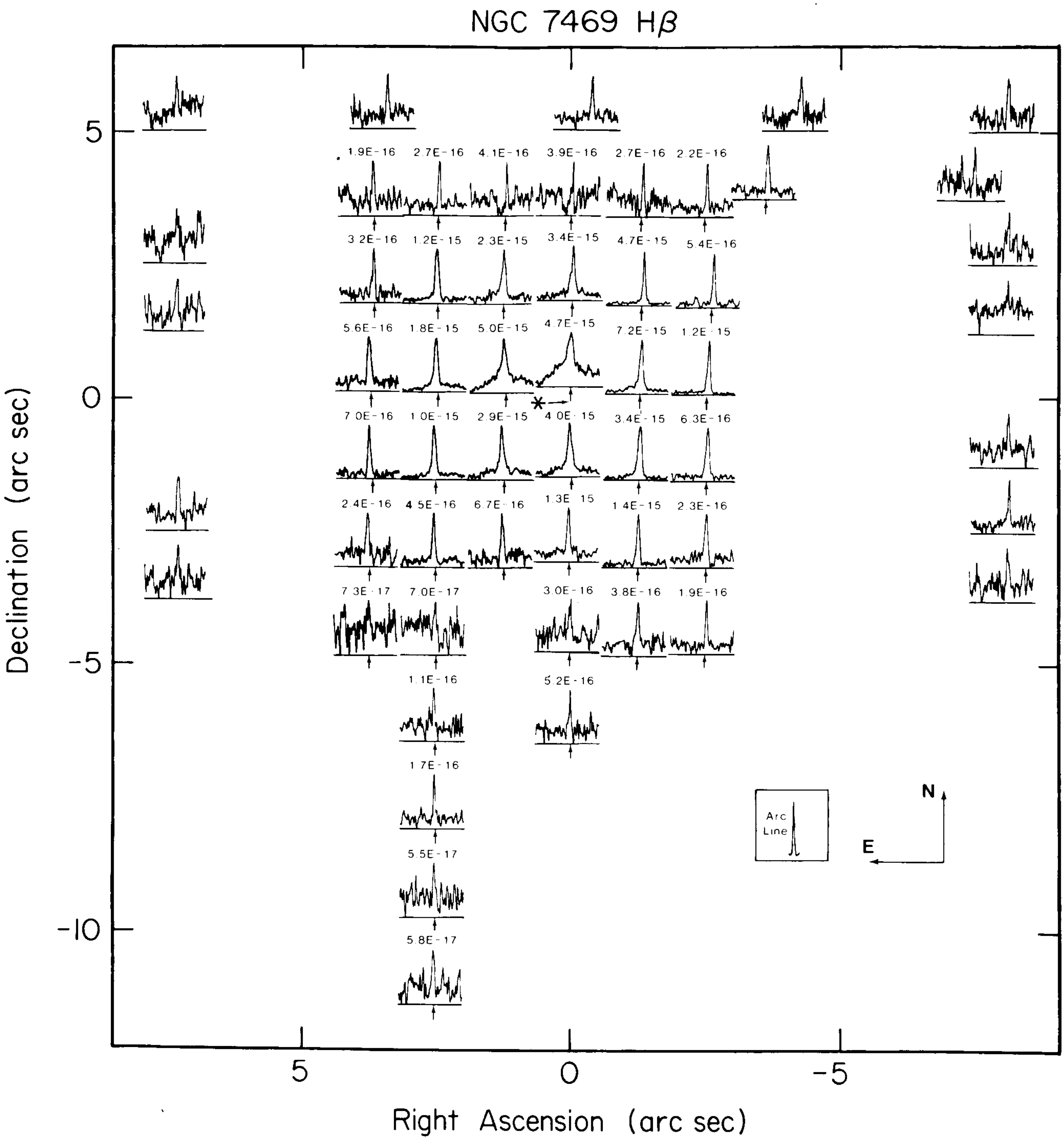

Figure 2b - Profiles of Hβ in NGC 7469; see caption to Fig. 2a and Wilson et al. (1986) for further details.

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c) The observed excitation ratio [OIII]λ5007/Hβ decreases from 7.5 at the nucleus to < 1 at the edge of the nebulosity, indicating an increasing relative contribution from the HII regions towards larger radii.

d) The recession velocity of the lines at the nucleus tends to be below systemic, as defined by the mean of the flat portions of the rotation curve or the HI 21 cm single dish line profile. Both this blueshift and the nuclear linewidth are higher for [OIII] than for [NII], and higher for [NII] than for Hα. This asymmetric location of the nucleus in the velocity curve and the different nuclear linewidths of the different species reflect a mixture of the high excitation, broad blueshifted component and the low excitation, narrow rotating component, the relative contributions of each component varying from line to line.

e) The total luminosity of hot stars has been estimated from the Balmer line emission of the low excitation component, and may approach the luminosity of the mid/far infrared emission of NGC 7469, as measured by IRAS. The spectral shape of this infrared emission is typical of galaxies with nuclear HII regions (see Section 2.4), and differs from most Seyferts, supporting the idea that it represents emission from dust heated by the hot stars. In NGC 7469, then, we have a case in which the infrared luminosity of the starburst overwhelms the infrared luminosity of the type 1 Seyfert nucleus.

Fig. 3 shows part of a long slit spectrum of Mark 315, another galaxy with two components of extended emission line gas. The different structures of Hβ and [OIII]λλ4959, 5007 are clearly apparent. Other Seyferts known to have composite circumnuclear spectra include NGC 1365 (Phillips et al. 1983a), NGC 7582 (Morris et al. 1985), and Mark 509 (Phillips et al. 1983b).

2.2 Radio Continuum Morphology

Ulvestad and Wilson (1984a, b) have mapped two samples of Seyfert galaxies with the VLA at 6 and/or 20 cm. The spatially well resolved sources may be classified as either "linear" (L) or "diffuse" (D). The L class sources, which are in the majority, comprise doubles straddling the optical continuum nucleus, triples or jet-like morphologies and are considered to be fuelled by the nonthermal active nucleus in a low power version of the radio galaxy phenomenon. These linear radio sources are morphologically associated with the high ionization narrow line region (e.g. Wilson 1986; Whittle et al. 1986) and are presumably unrelated to processes of star formation. The D class objects, of which only a handful are known, exhibit a "blob-like" radio morphology which appears not to be directly related to the nuclear activity itself. Figure 4 shows a comparison of isophotes in low excitation emission lines and radio continuum radiation for four of these D class objects. Each pair of maps of a given galaxy is reproduced to the same scale. The similarities in scale and morphology of the thermal and synchrotron emitting gases are striking. In all of these objects, the off-nuclear optical emission lines exhibit the two component structure noted above - a low excitation, rotating disk with narrow lines is seen superposed on a high excitation component in radial motion and showing broad lines. The D class radio sources are thus associated with the starburst, presumably representing the integrated effects of multiple supernovae and supernova remnants (e.g. Condon et al. 1982; Ulvestad 1982). It is important to bear in mind that some of the D class sources may also contain more compact radio emission which is fuelled by the Seyfert nucleus. The

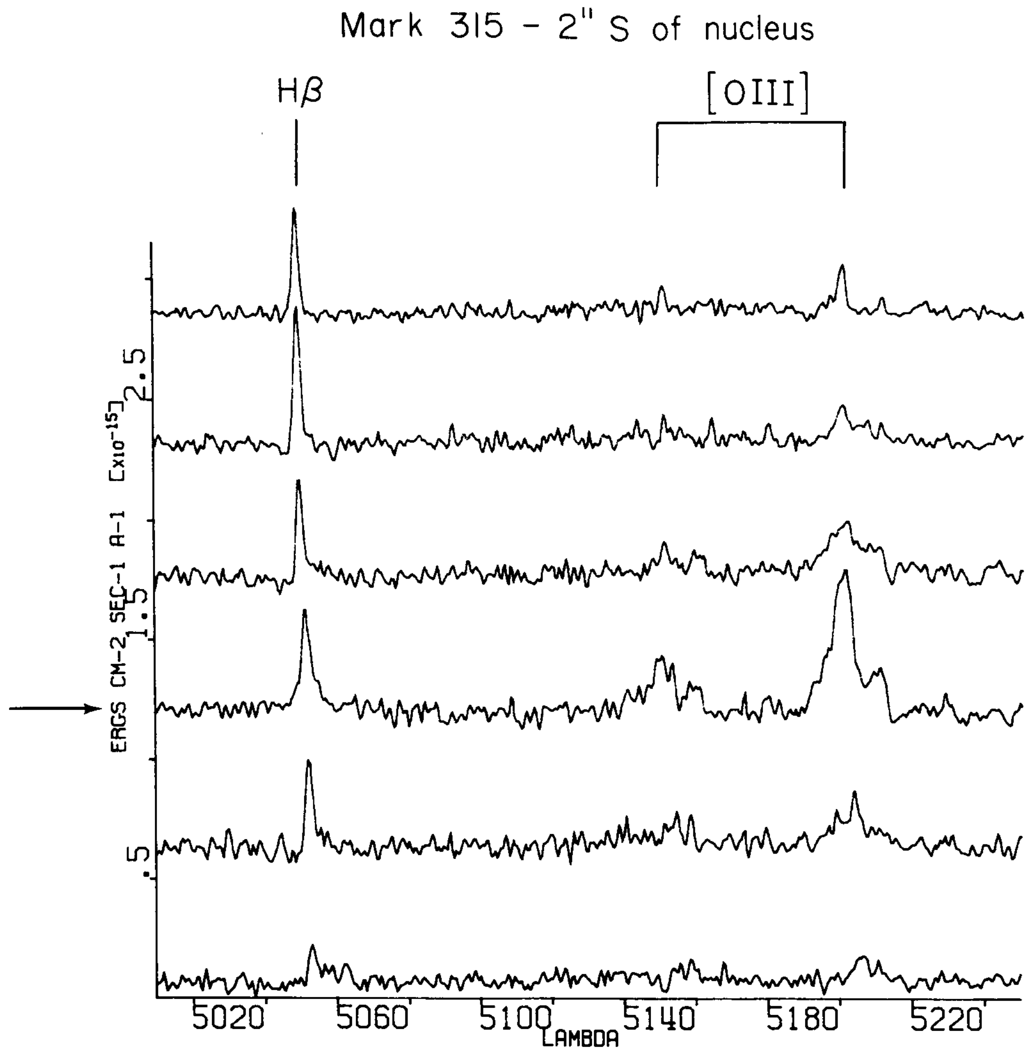

Figure 3 - Part of a long slit spectrum of Mark 315. The slit was oriented east-west and displaced 2" south of the nucleus. The individual spectra shown are separated by 1".65 along the slit and the spectrum which is closest to the nucleus is indicated by the horizontal arrow on the left (from A.S. Wilson and J.A. Baldwin, in preparation).

classic galaxy with both L and D class radio sources is NGC 1068, in which a 13" jet-like source is projected inside a starburst disk (Wilson and Ulvestad 1982, 1983; Wynn-Williams, Becklin and Scoville 1985). Also NGC 7469 and NGC 7582 show unresolved radio sources which are coincident with the optical nucleus and are probably associated with the nuclear activity proper.

2.3. Dust Emission Features

Aitken and Roche (1985) have pointed out the existence of prominent emission features due to gas and dust in the 8-13 μm spectra of starburst nuclei and the general lack of these features in the nuclei of active galaxies. It is noteworthy, however, that several of the Seyferts deduced above to possess circumnuclear starbursts do show dust emission features.

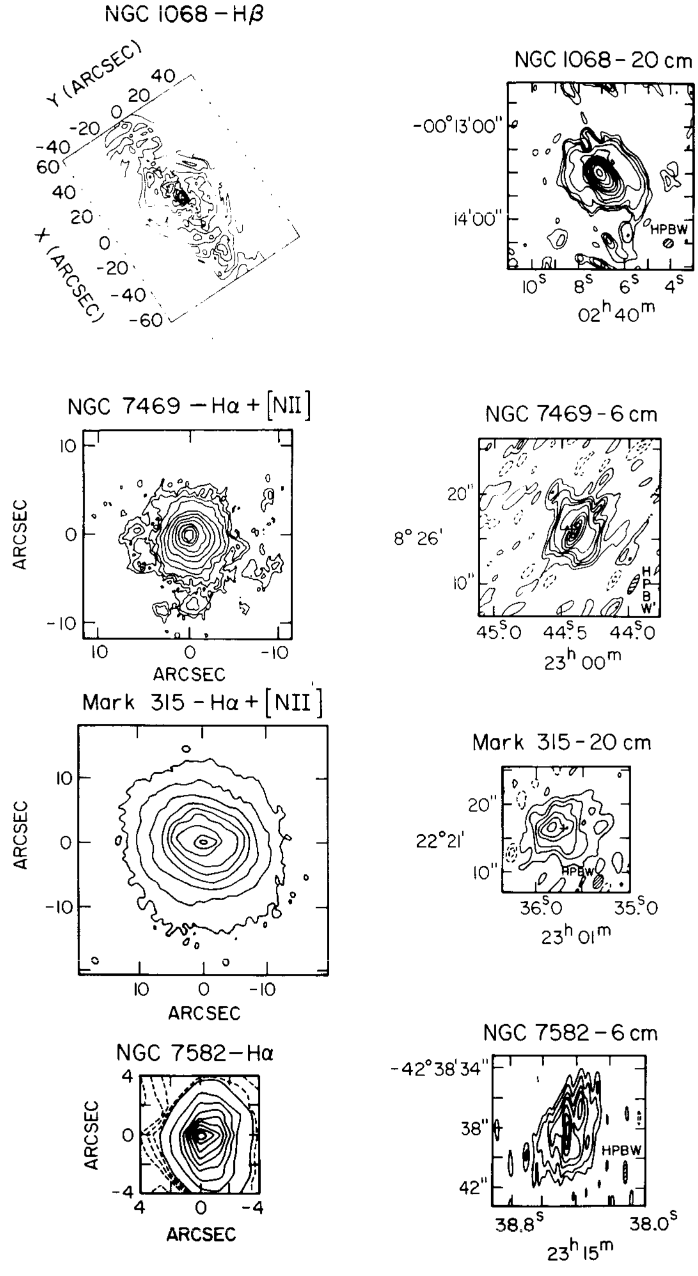

Figure 4 - Seyfert galaxies with circumnuclear starbursts. The left column shows the continuum subtracted isophotes of either Hβ, Hα or Hα + [NII]λλ6548, 6584. On the right is given contours of nonthermal radio emission at either 6 or 20 cm. Each pair of diagrams of a given galaxy is drawn to the same scale. A close morphological similarity between the two types of emission is evident. NGC 1068 (Seyfert type 2) - Hβ isophotes from Baldwin, Wilson and Whittle (1986), 20 cm isophotes from Wynn-Williams, Becklin and Scoville (1985); NGC 7469 (Seyfert type 1) - Hα + [NII] isophotes from Heckman et al. (1986), 6 cm isophotes from Ulvestad, Wilson and Sramek (1981); Mark 315 (Seyfert type 1) - Hα + [NII] isophotes from MacKenty (1986), 20 cm isophotes from Ulvestad, Wilson and Sramek (1981); NGC 7582 (Seyfert type 2) - Hα and 6 cm isophotes from Morris et al. (1985). These references should be consulted for the contour levels.

These galaxies include NGC 1365 (Aitken and Roche 1985), NGC 7469 (Aitken, Roche and Phillips 1981; Rudy et al. 1982; Cutri et al. 1984) and NGC 7582 (Roche et al. 1984). In at least NGC 1365 and NGC 7469, the dust emission features are spatially extended on the scale of the starburst, as determined from the distributions of radio continuum and low excitation optical emission lines. These dust emission features then clearly result from dust heated by hot stars, not from the active nucleus.

2.4. Far Infrared Spectra

Miley, Neugebauer and Soifer (1985) have investigated the far infrared (IRAS) colors of Seyferts by plotting the spectral index between 60 and 25μm against that between 100 and 60μm (Fig. 5a; spectral index α defined by $S \propto \nu^{\alpha}$). They find that, although Seyfert galaxies scatter widely in this plot, they have spectra which are much flatter (bluer), particularly between 60 and 25μm, than those of non-active spirals. Different species of emission line galaxy are found to have different spectral characteristics. Seyfert 1 galaxies are distributed widely in Fig. 5a, but the lower right (steeper spectrum between 60 and 25μm than between 100 and 60μm is populated mainly by objects with Seyfert 2 and nuclear HII region spectra. In histograms of the spectral curvature parameter, $\alpha(60,25) - \alpha(100,60)$, the Seyfert 1's distribute evenly about zero, while the Seyfert 2 distribution shows a preference for negative values, and the nuclear HII region spectra are even more curved (see Fig. 5a). Miley, Neugebauer and Soifer (1985) discussed these trends in terms of a mixture of three components - (i) a cold (~ 30K) disk component having spectral indices similar to those of "normal" spirals, (ii) a nonthermal nuclear component with a power law spectrum, and (iii) a mid infrared nuclear component which is probably thermal in origin and is located within the central hundred parsecs of the nucleus. If this last component does represent heated dust, the heating source could be either the nonthermal nuclear continuum or hot young stars. The segregation, albeit with a good deal of overlap, between the Seyfert 2's and the nuclear HII regions, implies a different distribution of dust temperatures between these two classes. Examination of Fig. 5a suggests the infrared spectra of nuclear HII regions lie within the zone $\alpha(60,25) < -1.5$ and $\alpha(100,60) > -1.1$. It is then of interest to ask whether the Seyfert galaxies in or near this zone also possess circumnuclear HII regions with hot star-heated dust contributing to or dominating the infrared emission.

Figure 5b shows a similar diagram in which only Seyfert galaxies known to possess off-nuclear HII regions are plotted. It should be emphasized that no attempt was made to select any particular spatial scale; the HII regions may be circumnuclear or in the galaxy disk. Also the study has not been made to any particular line flux level, nor were the galaxies selected in any well defined manner. The points in Fig. 5b show a considerable amount of scatter which presumably reflects differing ratios of nonthermally generated nuclear radiation (synchrotron radiation or dust heated by it) to that from dust heated by hot stars, either in the disk of the galaxy or in a circumnuclear starburst. It seems likely that the exact location of a Seyfert galaxy in this diagram is simply a function of the relative strengths of these two processes, the points lying along a "mixture band" joining the Seyfert nucleus and star-heated dust regimes. High spatial resolution infrared mapping is needed to confirm this hypothesis. The diagram confirms the dominance of a nuclear starburst in generating the far infrared emission of such objects as

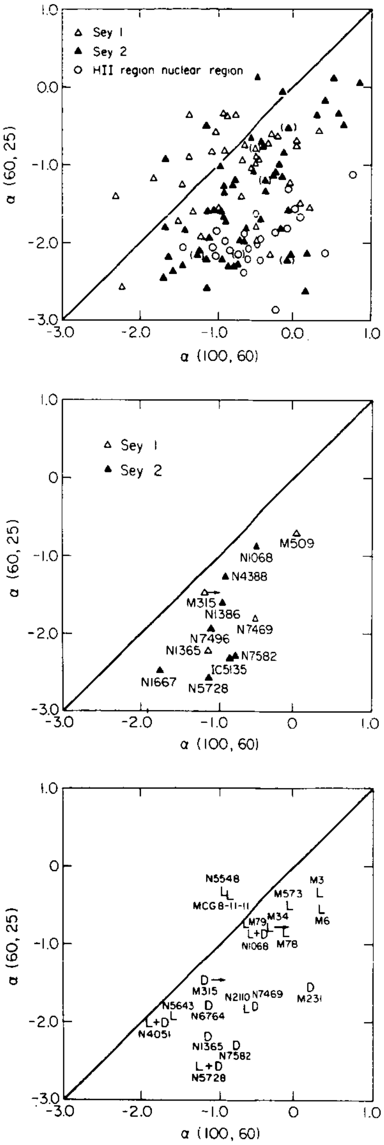

Figure 5 - Plots of the spectral index between 60 and 25μm [α(60,25)] vs. that between 100 and 60μm [α(100,60)] for Seyfert galaxies and nuclear HII regions following Miley, Neugebauer and Soifer (1985). a) Seyfert galaxies and nuclear HII regions listed in "Cataloged Galaxies and Quasars Observed in the IRAS Survey (1985)." b) Seyfert galaxies which are known to have circumnuclear HII regions. The references for the existence of HII regions are given in Section 2.1, when published. Unpublished long slit spectroscopy of Hβ and [OIII]λλ4959, 5007 by Wilson and Baldwin has also been used. c) Seyfert galaxies with known radio structural class. The symbol L refers to "linear" structure, the symbol D to "diffuse" structure and the symbol L+D is used for galaxies with both linear and diffuse components. Most structures are from our series of Ap. J. papers on radio properties of Seyfert galaxies (Ulvestad and Wilson 1984b being the most recent), plus Ulvestad and Wilson (1986, for MCG 8-11-11), Morris et al. (1985, for NGC 5643), Sandqvist, Jorsäter and Lindblad (1982, for NGC 1365) and Phillips, Wilson and Baldwin (unpublished, for NGC 5728).

NGC 7469 (a type 1 Seyfert) and NGC 7582 (a type 2).

In Figure 5c I plot the far infrared color-color diagram for Seyferts with established radio morphology. By and large, the infrared spectral properties correlate well with the radio morphology. The objects with both $\alpha(60,25)$ and $\alpha(100,60)$ greater than -1 tend to contain linear radio sources and their infrared emission seems to be dominated by nuclear activity. Several of them (e.g. Mkn 3, 78) have spatially very extended optical emission lines of high excitation, reflecting ionization by a central nonthermal source. If the far infrared emission were shown to be spatially extended in these objects, the most likely origin would involve dust coexistent with this extended narrow line region and heated directly or indirectly by the central nonthermal source. Alternatively, very compact infrared emission would likely be of synchrotron origin. Only 1 out of the 9 objects with $\alpha(60,25) > -1$ - NGC 1068 - shows evidence for a starburst. As already noted, the radio emission of NGC 1068 exhibits both a "linear" jet-like source and a "diffuse" galaxy-wide disk component.

In contrast to the flat infrared spectra of the "linear" sources, 8 out of the 10 galaxies with $\alpha(60,25) < -1.4$ show a "diffuse" radio component. Although 4 out of these 10 contain "linear" radio sources, I conclude that their infrared emission is likely radiated by dust heated by the hot stars, and is not directly related to the nonthermal active nucleus. A Wilcoxon rank-sum test indicates that $\alpha(60,25)$ is larger (60-25μm spectrum flatter) for L than for D type sources at the 99.8% confidence level, if the L+D's are included with the D's, or at the 96% confidence level, if the L+D's are included with the L's. The trend for the L's to have flatter 100-60μm spectra than the D's is much less significant. This infrared spectral distinction between L and D class objects is not related in a simple way to Seyfert type; both radio morphology classes contain both types 1 and 2.

The IRAS detectors were larger at longer wavelengths, with typical sizes of 0.'76x4.'6 at 12 and 25μm, 1.'5x4.'75 at 60μm and 3'x5' at 100μm. If the significant infrared emission is spread over scales larger than the smallest aperture, the spectra obtained will be too steep because of the extra emission in the long wavelength aperture. It is, therefore, important to check that the distribution of points in Fig. 5c is not strongly influenced by this effect. The mean redshift for the flat spectrum group ($\alpha(60,25) > -1.0$) in Fig. 5c is 6695 ± 3925 km s^{-1} (population standard deviation, not standard deviation of mean), while that for the steep spectrum group ($\alpha(60,25) < -1.4$) is 4134 ± 4072 km s^{-1}. Thus the difference in mean distances is such that the nearer objects have steeper spectra, in the expected sense for the resolution effect. The mean apparent spectral index for the flat spectrum group is $\alpha(60,25) = -0.60 \pm 0.20$ and that for the steep spectrum group $\alpha(60,25) = -1.95 \pm 0.32$, with the quoted errors again being the population standard deviation. Attribution of this difference of mean indices completely to a resolution effect would require $\simeq$ 68% of the observed flux of the steep spectrum objects at 60μ, to originate from scales intermediate between the 25 and 60μm apertures, if the flat spectrum objects are spatially unresolved at both wavelengths. If the flat spectrum objects are also partially resolved at 25μm, this percentage becomes larger. While we have little direct information on the true spatial extent at these wavelengths, the mean difference in distances of the two groups is probably not large enough to ascribe their different infrared colors to resolution effects.

3. CONCLUSIONS

I have shown that star formation - either circumnuclear or in the galaxy disk - in Seyfert galaxies can be diagnosed through a number of observations. First, spatially resolved optical spectroscopic studies can distinguish the narrow, low excitation emission lines of HII regions from the broad, high excitation emission of the Seyfert nucleus. Either the line ratios or the kinematic properties of the gas may be used to separate the two components, the latter method relying on the result that the HII regions generally lie in a rotating, flattened system, while the gas ionized by the Seyfert nucleus follows radial motion (inflow or outflow). Second, an extended, "diffuse" or "blob-like," nonthermal radio source is observed in a minority of Seyfert galaxies and probably represents the integrated radiation of multiple supernova remnants generated by the starburst. This morphology may be contrasted with the "linear" (double, triple or jet-like) radio structure associated with the nuclear activity proper. Third, regions of star formation generally exhibit emission features of gas and dust in the 8-13μm spectral range, while these features tend to be absent in Seyfert nuclei (Aitken and Roche 1985). Seyfert galaxies which do show these features contain circumnuclear starbursts. Fourth, the IRAS band colors of Seyfert galaxies seem to correlate with the presence or absence of star formation. Seyferts with prominent disk or circumnuclear star formation show steep spectra between 25 and 60μm ($\alpha(60,25) < -1.4$) and flatter spectra between 60 and 100μm. The far infrared emission of Seyferts without significant star formation is dominated by the active nucleus and may represent direct incoherent synchrotron radiation or dust heated by it. Such galaxies show flat spectra ($\alpha > -1$) over the 25-60-100μm band. It seems likely that the far infrared colors of any given Seyfert galaxy are primarily a function of the relative strengths of the hot-star and nuclear-powered components.

It is notable that $\leq$ 20% of well resolved, circumnuclear radio sources in Seyfert galaxies are dominated by the "diffuse" component. This result provides a crude limit on the occurrence of very intense circumnuclear star formation. A similar statement cannot be made for the disk component, because our radio measurements were made mainly in the ´A´ configuration of the VLA and are relatively insensitive to very extended radio emission. Our result is, however, entirely consistent with the conclusion of Roche and Aitken (private communication) who find that < 10% of Seyferts show dust emission features.

In order to assess whether star formation is more prevalent in Seyfert galaxies than in otherwise similar, non-active galaxies, we need to construct a luminosity function of some measure of the star formation in both Seyferts and a comparison sample. Such a luminosity function was shown at this meeting by Rieke, who assumed that excess infrared emission seen by the low resolution IRAS detectors, in comparison with ground-based photometry through a small aperture, was indicative of star formation. If it is true that the effects of the active nucleus are entirely confined within the few arc sec apertures typical of ground-based infrared observations, Rieke's luminosity function indicates an excess of star formation in Seyferts over normal spirals. This conclusion should be checked using some of the other indicators of star formation that I have described.

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DISCUSSION

EDELSON:

Two comments:

1) The Miley, Neugebauer and Soifer result you quote, that Seyfert 1s, Seyfert 2s, and HII regions lie in different regions of color-color diagrams, becomes even clearer when optically selected AGNs are used.

There is a strong tendency for objects along the sequence quasar–SY1–SY2–HII regions to have increasingly steep slopes, presumably due to a larger ratio of thermal/non-thermal luminosity.

2) Our studies of optically selected Seyferts show a tight correlation (at the 99.99% confidence level) between L_{IR} and L_{RAD} for Seyfert 1s, and a weaker one (99.95% confidence level) for Seyfert 2s. These results confirm the hypothesis that the far-infrared emission from most quasars and low-reddening Seyfert 1s is primarily non-thermal in origin, while that from Seyfert 2s and other AGNs with high dust indicators is primarily thermal.

WILSON:

1) The Miley, Neugebauer and Soifer result is for optically selected AGN's.

2) We still don't have a convincing explanation for this well known correlation in Seyfert galaxies. It is very dangerous to assume that the 60 and 100μm IRAS observations of Seyferts are dominated by the nucleus. As I have tried to show, the far-infrared emission from circum-nuclear or extra-nuclear star forming regions overwhelms the emission from the nucleus in a significant fraction of Seyfert galaxies. The IRAS flux can be either be nuclear dominated or disk/starburst dominated, the exact ratio varying from galaxy to galaxy. This effect must first be sorted out before the IRAS data can be used to study the emission mechanism of the nucleus.

CUTRI:

Based on your kinematical studies, can you determine whether the extended HII regions are physically distinct from the narrow-line emitting region, or could there be a transition region which might imply that the two share common material?

WILSON:

Generally speaking, we can account for the kinematic and ionization properties in terms of a mixture of a Seyfert-like component and a normal HII region component, the relative proportions of the mix varying from place to place. It's very difficult to pick out gas which has a true intermediate spectrum. There is, however, a hint that the sources of gas in the two components may be related since the high-excitation and low-excitation morphologies are sometimes similar.

SARGENT:

There is a further diagnostic for circum-nuclear starbursts in Seyferts. High resolution (6") CO observations of NGC7469 made with the Owens Valley Millimeter Wave Interferometer show that the molecular gas is offset from the nucleus and is more or less coincident with the narrow emission line region.

WILSON:

High-resolution interferometric CO maps will, indeed, be a most valuable technique for identifying circum-nuclear starbursts. I look forward to seeing more of these fascinating results and their relation to the other diagnostics I mentioned.

BEGELMAN:

In NGC 1068, there is a compact thermal IR source which probably results from reradiation of the non-thermal continuum, in addition to a larger component, associated with the starburst. What are the prospects for distinguishing between these two components in other objects?

WILSON:

Quite good, I think. In NGC 1068, the compact (arc sec) nuclear component is the hotter one and the extended, cooler component is associated with the 'starburst' disk (Telesco *et al.* 1984, *Ap.J.*, **282**, 427). Comparison of ground based measurements at 10μm and 20μm made with a small aperture with the large aperture IRAS measurements at 12μm and 25μm can separate nuclear and disk components in other galaxies. I have shown how a disk or circum-nuclear 'starburst' component of the IRAS fluxes in Seyfert galaxies can be identified via optical line studies, radio continuum mapping, infrared spectroscopy near 10μm and the IRAS spectral shape itself. All of these methods can be used to separate nuclear from non-nuclear components in active galaxies.