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RECOMBINATION SPECTROSCOPY OF STAR-FORMATION REGIONS IN THE NUCLEUS OF M83

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ABSTRACT

The Brα (4.05 μm) and Brγ (2.17 μm) recombination lines of ionized hydrogen have been observed in five positions in the nucleus of M83 and detected in two. The results show that young OB stars are the major source of energy in the nucleus and that the extinction toward the young stellar region is high ($A_v = 15$–30 mag) and spatially patchy. The Brackett lines are anomalously strong relative to the thermal radio flux. Possible explanations for this unexpected result are very low electron temperatures or a population of compact H II regions in the nucleus. In the latter case, we suggest that the starburst must be extremely short-lived (10^4 yr) and not likely to be sustained.
Subject headings: galaxies: individual — galaxies: nuclei — infrared: spectra — nebulae: H II regions — stars: formation

I. INTRODUCTION

We have been engaged in a study of star formation in external galaxies using infrared spectroscopic observations of the ionized hydrogen in galactic nuclei. Results on other galaxies have been discussed in a previous paper (Beck, Turner, and Ho 1986). The spiral galaxy M83 was found to present special problems and is therefore discussed separately here.

Infrared spectroscopy has proved to be invaluable in studies of star formation in both Galactic and extragalactic sources (Lacy 1980; Beck, Beckwith, and Gatley 1984). Spectral lines such as the Brα and γ transitions of hydrogen can penetrate the dust found in star-forming regions and are free of contamination by nonthermal emission processes, an important consideration in external galaxies. The hydrogen lines are produced copiously in the dense, young H II regions of newly formed OB stars, so their presence in a galaxy is an excellent diagnostic of recent star formation. The line strengths can be used to derive an accurate measure of the OB stellar population as well as the spatial distribution and the strength of the starburst.

M83 (NGC 5236) is a promising object for such studies. It is a luminous, nearby (3.7 Mpc; de Vaucouleurs 1979) SBb/SBc galaxy. M83 has a particularly bright optical nucleus, as noted by Sérsic and Pastoriza (1967), which is also dominant in the ultraviolet (Bohlin *et al.* 1983). Strong, extended ($\gtrsim 15''$) 10 μm emission is observed in the nucleus (Rieke 1976), with a far-infrared spectrum similar to that of M82 (Telesco and Harper 1980; Hildebrand *et al.* 1977). Extended nuclear radio (Condon *et al.* 1982) and X-ray (Trinchieri, Fabbiano, and Palumbo 1985) emission have been observed, as well as CO and C^+ emission, which indicate the presence of substantial amounts of molecular material in the nucleus (Rickard *et al.* 1977; Crawford *et al.* 1985). All of these observations suggest that vigorous star formation is now taking place in the core of M83.

The observations of M83 and their analysis are described in § II. Although the infrared recombination lines and radio continuum are both direct measures of the Lyman continuum flux, serious disagreements were found between the radio and infrared measurements. The unexpected excess Brackett line strengths compared to the observed radio continuum emission implies unusual conditions in the nuclear environment of M83. This is discussed in § III.

II. OBSERVATIONS AND ANALYSIS

The observations were made on the NASA Infrared Telescope Facility on Mauna Kea on 1985 March 16. The instrument used was the Cornell cooled grating spectrometer (see Beckwith *et al.* 1983, for description) with a 7″.2 beam and spectral resolution ~1/800. In each spectrum, seven to nine independent wavelengths spaced by $\frac{1}{2}$ resolution element were measured, and, in all positions except one, two independent spectra were obtained. Wavelength calibration by laboratory lamp lines was checked by measuring the Brackett lines in W51. The flux calibration is based on observations of standard stars and has absolute accuracy ±10%. The relative accuracy of different spectra is about ±4%. Positions were acquired by offsetting from SAO stars and checked by returning to the star every 15 minutes and are accurate to ±1″. The Brα line was sought in five positions and detected in two. The Brγ line was observed only in the positions where Brα was found, since the latter is expected to be stronger in heavily obscured regions such as galactic nuclei. Infrared beam positions are shown in Figure 1 superposed on an Hα photograph of M83. The observed spectra are shown in Figure 2. Line and continuum fluxes and upper limits are listed in Table 1.

The extinction at the 2.17 μm and 4.05 μm wavelengths of Brγ and Brα is much less than in the visible but can be significant. This is especially true in galaxies, where an attempt to look deeply into the central regions is virtually certain to

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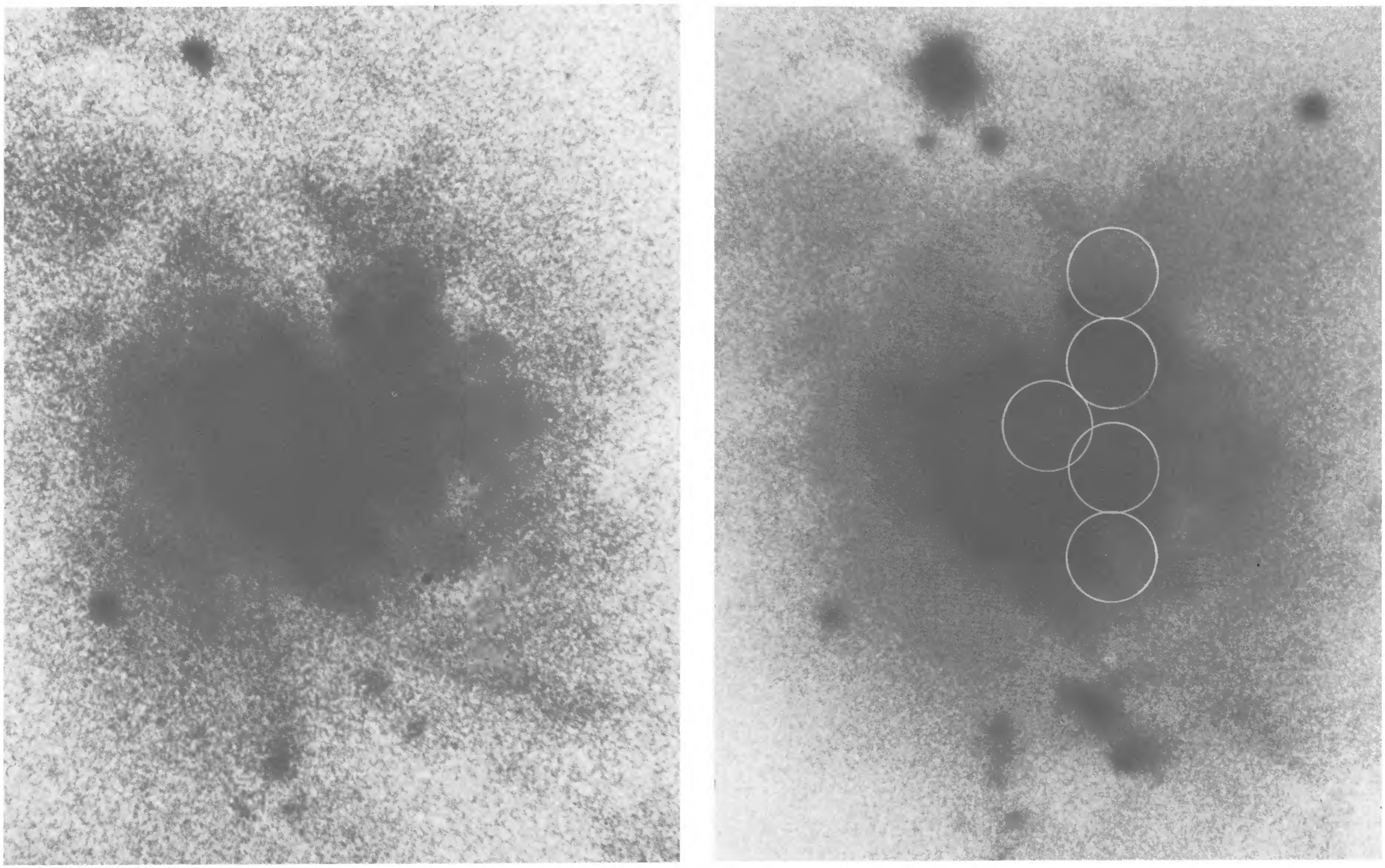

FIG. 1.—*Left*: The M83 nuclear region as it appears in the V band. The photograph was made from a plate taken at the CTIO 4 m telescope by Talbot and Dufour, on a 103 a-D emulsion, GG 495 filter with a 10 minute exposure (see Talbot, Jensen, and Dufour 1979). *Right*: The infrared beams and observed positions are overlaid on an Hα photograph (Talbot and Dufour, CTIO 4 m, 127-02 emulsion, λ6565 120 Å FWHM filter, 60 minute exposure) of the M83 nucleus, at the same scale as the continuum photograph. The infrared beams are 7″.2 FWHM, which corresponds to 130 pc at the assumed distance of 3.7 Mpc. Registration of the infrared and optical positions was accomplished by identifying the two H II regions to the north and east of the nucleus in the catalog of Rumstay and Kaufman (1980). Errors in registration are roughly ±1″.

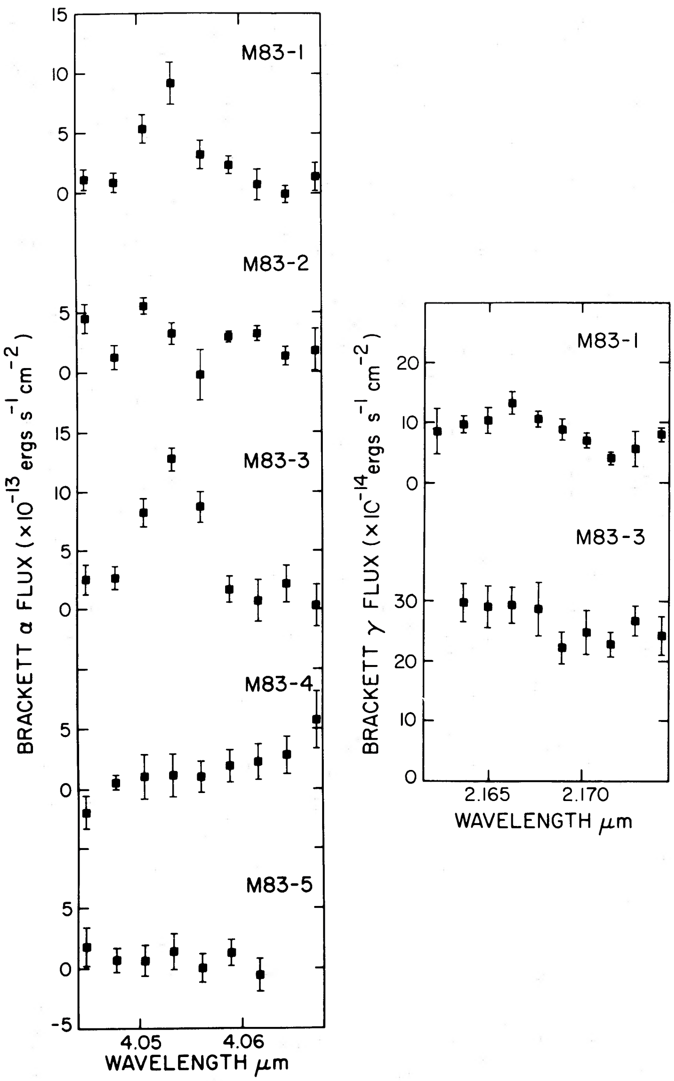

FIG. 2.—*Left*: Brα spectra. *Right*: Brγ spectra. Error bars represent ±1 σ uncertainties. The spectral resolution is $\Delta\lambda/\lambda \sim 1/800$ or $\sim$375 km s^{-1}. The central data point has been set at the systemic velocity of M83, 500 km s^{-1}; slight offsets of the lines in wavelength are due to flexure of the grating mounting within the dewar. Reported fluxes correspond to integration over one resolution element.

encounter very high obscuration, even in cases where measurements at shorter wavelengths, which do not see in deeply, find low extinction. An advantage of observing both of the Brackett lines is that they can be used to determine and correct for the infrared extinction. The flux ratio of Brα to Brγ can be predicted from recombination theory and compared to the observed ratio: the discrepancy gives the reddening or differential extinction between 2.17 and 4.05 μm directly. The total extinction at one wavelength can then be found if the extinction law is known. The theoretical Brα to Brγ line ratios are not very sensitive to density over the range likely for H II regions. However, they do increase significantly with lower electron temperatures (Brocklehurst 1971; Giles 1977; Osterbrock 1974). Since there are no direct measurements of the electron temperature in M83 available, we adopt $T_e = 5000$ K, the lowest temperature for which the recombination coefficients have been calculated. Low electron temperatures, presumably due to higher metallicities and hence cooling, have been inferred for our own Galactic center (Churchwell *et al.* 1978; Peimbert, Torres-Peimbert, and Rayo 1978; Garay and Rodríguez 1983), and others (Aller 1942; Peimbert 1968; Searle 1971). At 5000 K, the theoretically predicted ratio of Brα to Brγ flux is 3.1. In positions where both Brackett lines were measured, the differential extinction A_γ–A_α was derived, and then A_α was found by application of a $\lambda^{-1.9}$ reddening law. Both results are listed in Table 2.

The total ionizing flux can be found from the extinction-corrected Brackett line strengths and recombination theory. At 5000 K, 1 Brα photon is emitted for every 10 Lyman continuum photons absorbed. The ionizing flux, $N_{\rm Lyc}$ (s^{-1}) = $2.7 \times 10^{63} D_{\rm Mpc}{}^2 S_{\rm Br\alpha}$ (ergs cm^{-2} s^{-1}), in each position is given in Table 2. The total luminosity of the young stars responsible for the ionization can be estimated if an initial mass function and mass cutoffs are assumed. Using a Miller and Scalo (1978) IMF with mass cutoffs at 30 $M_\odot$ and 5 $M_\odot$ gives $L_{\rm OB} = 4.7 \times 10^{-44} L_\odot N_{\rm Lyc}{}^{-1}$. The total luminosity from young stars is shown in Table 2 for each beam position.

We also compare the Brα and radio continuum fluxes. The integrated Brα line flux can be used to predict the thermal radio emission with $S_{15\,\rm GHz}$(Jy) = $1.88 \times 10^{10} S_{\rm Br\alpha}$ (ergs cm^{-2} s^{-1}). To estimate the observed thermal radio flux, we use the 1″ resolution 15 GHz and 5 GHz VLA maps of Turner and Ho (1987). The radio maps were convolved with a 7″.2 Gaussian to match the infrared beam. We assume an intrinsic spectral index of −0.1 for the thermal component of the emission, and a nonthermal component with spectral index of −1.0. Thermal contributions to the radio fluxes were then estimated from the measured spectral indices, in Table 1. Since the assumed nonthermal spectral index is steep compared to typical Galactic values, the deduced thermal fluxes may be overestimates. The predicted thermal radio fluxes are listed in Table 2.

Possible sources of uncertainty in our analysis include the T_e

TABLE 1

OBSERVED INFRARED AND RADIO PROPERTIES

Position	Offset[a] (E″, N″)	F_α (10^{-13} ergs cm^{-2} s^{-1})	4 μm Continuum (Jy)	F_γ (10^{-14} ergs cm^{-2} s^{-1})	2 μm Continuum (Jy)	Total 15 GHz Flux (mJy)	Estimated Thermal 15 GHz Flux[b] (mJy)	Spectral Index[c] ($\alpha_{15\,\rm GHz/5\,GHz}$)
M83-1............ (radio peak)	(0, 0)	7.5 ± 1.1	0.1 ± 0.1	6.2 ± 1.6	0.04 ± 0.01	20	14	−0.5
M83-2............	(5, −5)	≤2.8	0.3 ± 0.1	...	...	19	17	−0.2
M83-3............	(0, −9)	11 ± 1.1	0.2 ± 0.1	≤4.8 ± 1.6	0.15 ± 0.015	10	8	−0.4
M83-4............	(0, 7)	≤2.8	0.2 ± 0.2	...	...	5	3	−0.6
M83-5............	(0, −16)	≤2.8	0.1 ± 0.1	...	...	4	3	−0.3

[a] The origin, M83-1, is located at $\alpha = 13^{\rm h}34^{\rm m}11^{\rm s}.09$, $-29°36'35''.0$.

[b] Assuming thermal spectral index of −0.1, and nonthermal component with spectral index −1.0.

[c] Observed spectral index is defined as $S \propto \nu^\alpha$, derived from 15 GHz and 5 GHz continuum maps of Turner and Ho 1987.

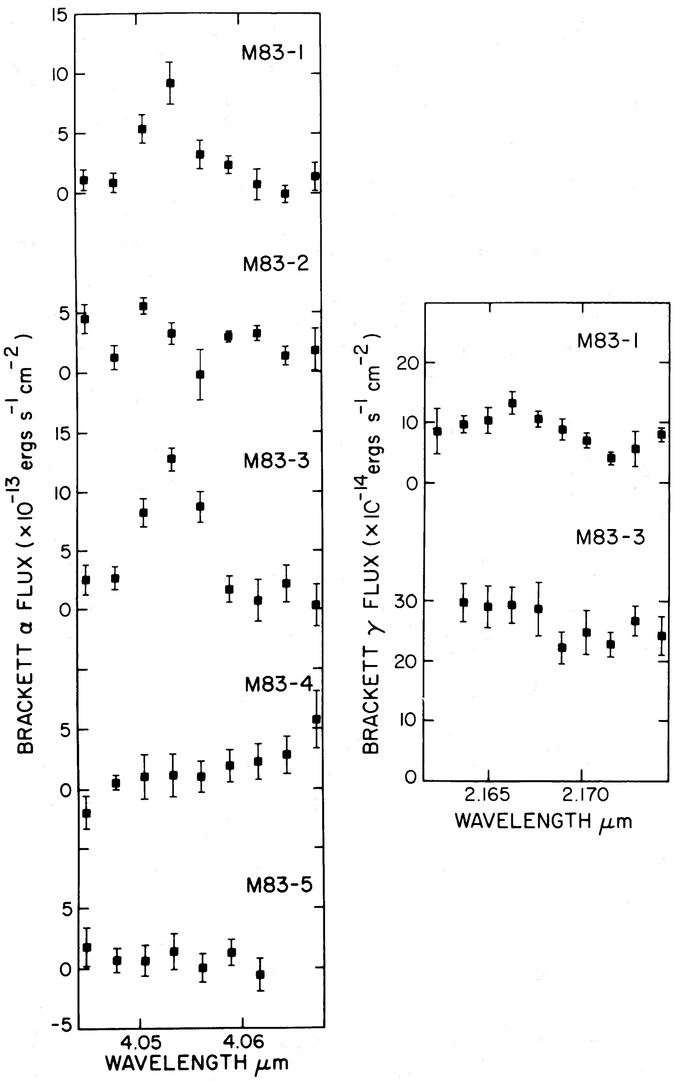

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TABLE 2

DERIVED PROPERTIES

Position	$A_\gamma - A_\alpha$	A_α[a]	$F_{\alpha\,\rm corr}$ (10^{-12} ergs cm^{-2} s^{-1})	Predicted 15 GHz Flux (mJy)	$N_{\rm Lyc}$ (10^{52} s^{-1})	$L_{\rm OB}$ ($10^9\ L_\odot$)
M83-1..........	1.5	0.66	1.4	26	5.2	2.4
M83-2..........	...	...	...	<5[b]	<1.0[b]	<0.47[b]
M83-3..........	≥2.2	≥0.96	≥2.7	≥51	≥10	≥4.7
M83-4..........	...	...	...	<5[b]	<1.0[b]	<0.47[b]
M83-5..........	...	...	...	<5[b]	<1.0[b]	<0.47[b]

[a] Assuming a $\lambda^{-1.9}$ reddening law.
[b] Assuming zero extinction at 4 μm.

assumed and the reddening law used. If T_e is in fact as high as 10,000 K, the Brα to Brγ ratio predicted will decrease by less than 10% and $N_{\rm Lyc}$ will increase by about 30%, but the $S_{15\ \rm GHz}$ predicted from a given Brα line strength will increase by ~80%. More serious uncertainties can enter in the assumed IMF. The total OB luminosity is insensitive to the lower mass cutoff but could be a factor of 2 lower if the upper mass cutoff is increased to 60 $M_\odot$. However, the presence of such high-mass stars would be inconsistent with the relatively low excitation implied by the strength of [Ne II] emission typically observed in spiral galaxies (Phillips, Aitken, and Roche 1984).

III. DISCUSSION

a) *Quantifying the Starburst*

The Brackett line fluxes confirm that the nucleus of M83 is a region of intense star formation. The OB stellar luminosity implied by the Brackett fluxes is 60% higher than the total observed infrared luminosity of $4 \times 10^9\ L_\odot$ (Telesco and Harper 1980, corrected for distance), which is good agreement considering the uncertainties in these luminosity derivations. From the Brackett fluxes we estimate that $\sim 7 \times 10^6\ M_\odot$ of young OB stars are present in the nuclear region. We conclude that OB stars produce most, probably all, of the infrared luminosity.

The 10 μm continuum fluxes observed in M83 can also be compared to those predicted from the Brackett line fluxes, if we assume that Lyman α heating is primarily responsible for the 10 μm dust emission. In the Galaxy, the observed relation of 10 μm flux to radio flux is $S_{10\ \mu\rm m} \sim 10 \pm 3\, S_{3\ \rm GHz}$ (Thronson, Campbell, and Harvey 1978; Lebofsky *et al.* 1978). Adopting this relation, we obtain $S_{10\ \mu\rm m} = 0.23 S_{\rm Br\alpha}(10^{-12}$ ergs cm^{-2} s^{-1}), with an uncertainty of ~30%. The observed 10 μm flux from M83 is 2.6 Jy in a 20″ beam (Rieke 1976) and is consistent with the total predicted 10 μm flux of ~0.9 Jy from M83-1 and M83-3, given the differences in beamsize. This is in contrast to the cases considered in our previous paper (Beck, Turner, and Ho 1986), where the 10 μm emission exceeds the predictions from Brackett lines by an order of magnitude. We conclude that M83 is a case where the 10 μm emission *is* consistent with Lyα-dominated dust heating, at Galactic-type dust temperatures of ~150–200 K.

The extinctions that we derive from the Brackett line ratios for the M83 nucleus are quite high. The deduced visual obscuration in the two detected positions is ~18 mag and 28 mag, for M83-1 and M83-3. In order to account for the deficiency in the Brackett lines compared to the thermal radio continuum at M83-2, the extinction must also be high, $A_v \gtrsim 14$ mag. The obscuration to the ionized gas is therefore much greater than the $A_v \approx 1$ obtained from the H_α/H_β measurements of Pastoriza (1975), or the 5 mag of Dufour *et al.* (1980) from H_γ/H_β and H_δ/H_β, but in closer agreement with the optical depth of 1.59, and implied $A_v \sim 35$, found for the 10 μm silicate feature by Lebofsky and Rieke (1979). These results suggest that the shorter wavelength observations sample only the outer layers of the dusty regions. It is not clear that we are seeing through the region even at 4 μm, since the extinction determination depends on the flux at 2 μm, which is clearly suffering a sizable attenuation ($A_{2\ \mu\rm m} > 2$). Finally, the extinctions derived at the two measured positions are different, which implies a patchy dust distribution toward the nucleus.

The comparison between the Brackett line fluxes and the observed radio continuum emission is difficult to interpret. As may be seen from Table 2, the line fluxes vary rapidly from point to point and in some cases do not appear consistent with the radio results. We emphasize that the derivation of thermal radio flux from the Brackett lines is straightforward and is independent of distance and geometry. Statistical and calibration uncertainties of the Brackett fluxes are completely inconsequential in the discrepancies which we have found. M83-1, the radio peak, has strong radio, Brα, and Brγ flux. However the estimated thermal radio emission is too low by a factor of 2 to be consistent with the expected value derived from the Brackett flux. In fact, even the *total* 15 GHz radio flux falls short by 30% of agreement with the Brackett fluxes. The possibility that we are underestimating the Brα flux due to extinction makes the discrepancy potentially more serious. In M83-3, the Brackett line and radio fluxes are in even more severe disagreement. The Brα luminosity is strong, 80% that of the entire nuclear region of NGC 253 (Beck and Beckwith 1984), and the Brγ line is not seen although the 2 μm continuum is strong. The implication is that the obscuration at this position is very high. However, the estimated thermal radio flux is too low by more than a factor of 6 to be consistent with the large body of highly obscured ionized gas indicated from the Brackett lines. The disagreement may in reality be even more serious since the extinction is a lower limit here. In the extreme and unlikely case that all of the 15 GHz flux is thermal and there is no extinction at 4 μm, the radio flux is still low by a factor of 5 compared to the Brackett lines. In M83-4 and M83-5 the null detections are consistent with the radio fluxes and moderate amounts of 4 μm extinction.

The anomalous ratio of the Brackett lines compared to the thermal radio flux is difficult to understand. The estimated experimental errors cannot account for the discrepancies. Statistical uncertainties on each point are, as can be seen from Figure 2, small. Nor does the explanation appear to lie in the division of thermal and nonthermal radio flux. In both positions where the Brackett lines were detected, even the total amount of observed radio flux is insufficient to be consistent with the Brackett fluxes. Moreover, the assumption that all of the radio flux represents thermal bremsstrahlung emission from the ionized gas would clearly contradict the spectral index observations. Mechanisms do exist that can suppress the radio emission relative to the infrared lines. The most likely mechanisms will be discussed in the next section.

b) The Anomalous Brackett to Radio Flux Ratios and the Nature of Star Formation in M83

The most unexpected result of the Brackett line observations is the inexplicably high ratio of Brackett line to radio continuum flux. The discrepancy by a factor of 6 in M83-3 cannot be explained by observational uncertainties. There are two situations seen in our Galaxy where the radio continuum flux can be suppressed relative to the infrared recombination lines. First, the temperature of the ionized gas in M83 may be cooler than the 5000 K used. The intrinsic ratio of Brα to Brγ would then increase, thereby lowering the derived extinction and corrected Brackett flux. The intrinsic Brα to radio flux ratio would also increase, lowering the predicted thermal radio flux. Enhanced heavy-element abundances from previous generations of stars may be responsible for increasing the cooling rate of the ionized gas, resulting in the low electron temperatures observed in galactic nuclei. Thus the conditions suggested above for the ionized gas may be the natural outcome of its location in the nuclear region. There are at present no calculated recombination coefficients for $T_e < 5000$ K, so it is not known what temperature is required or indeed if this explanation is viable.

The second possible explanation for the high Brackett line to radio flux ratios is that a substantial portion of the ionized gas is in compact or ultracompact H II regions. A region with emission measure EM $\sim 10^9$ cm^{-6} pc will have an optical depth of 1 at 15 GHz, thereby suppressing the radio emission. Such emission measures are characteristic of ultracompact (diameter < 0.1 pc) H II regions seen in the Galaxy (Habing and Israel 1979). A lower limit to the emission measure in M83 can be found by assuming the ionized gas producing the Brackett lines is uniformly distributed in spheres with diameters equal to that of our beam. This lower limit is about 10^5 cm^{-6} pc. If the sources of Brackett lines are clumped, the emission measure could well be high enough to cause the H II regions to be optically thick in the radio without affecting the Brackett lines. A possible model that could reproduce the Brackett and radio fluxes would be 10^2–10^3 compact H II regions within each beam. Thus the anomalous Brackett line to radio flux ratios could in principle be due to a population of optically thick compact or ultracompact H II regions.

Of the two models, the latter has the greatest implications for the star-formation process in the nucleus. Unless compact H II regions are confined, they are short-lived, with lifetimes $\sim 10^3$ to 10^4 yr. There are no obvious confinement mechanisms besides remnant envelopes, which are themselves unlikely to be very long-lived against stellar winds or nearby supernovae. Evidence for winds is indeed present in the blue-shifted, high-excitation atomic lines seen in the ultraviolet (Bohlin *et al.* 1983). In the absence of some other source of confining pressure, it is most likely that the H II regions are very young. This requirement of extreme youth for the sources of the Brackett line emission places stringent demands on the duration of the starburst. The mass of ionized gas and stars involved in the currently measured OB star activity is about 0.2% of the total mass of $4 \times 10^9\, M_\odot$ estimated for the spheroidal component of M83 by de Vaucouleurs, Pence, and Davoust (1983), yet the present phase is in this picture less than 10^4 yr old. If there were an earlier burst of star formation those stars should have developed through the compact H II region stage by now and be seen as strong contributors to the thermal radio flux, yet they are not evident. The tentative conclusions attendant on this model are therefore: (1) Nearly all of the current population of young stars in the nucleus are less than 10^4 yr old. (2) The star formation process in the nucleus of M83 cannot continue for many generations at the present rate before it ties up an unacceptably large fraction of the available material in stars and stellar remnants.

IV. CONCLUSIONS

Observations of the Brackett line emission from M83 show that star formation is the major source of luminosity in the nucleus of this galaxy. The extinction to the infrared-emitting gas is much higher than that found from optical observations since the infrared lines originate in deeper, optically obscured regions. The extinction varies from position to position, suggesting patchiness in the nuclear dust distribution. A surprising and at present unexplained result of these observations is the anomalously high ratio of Brackett line to radio flux measured. A possible explanation may be that the electron temperature is so low that the recombination coefficients calculated for 5000 K are inapplicable. It would be of great value to have recombination coefficients for temperatures $T_e < 5000$ K, which may be important in galaxies whose metal abundances have been enhanced by repeated star-formation activity. Another possibility is that the ionized regions are so young and dense as to be optically thick in the radio, which would imply an extremely short-lived burst. Radio measurements at shorter wavelengths could possibly distinguish such sources.

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