Brackett gamma observations and extinction in giant H II regions in M 101

Skillman, E.D.; Israel, F.P.

Citation

Skillman, E. D., & Israel, F. P. (1988). Brackett gamma observations and extinction in giant H II regions in M 101. *Astronomy And Astrophysics*, *203*, 226-232. Retrieved from https://hdl.handle.net/1887/7551

Astron. Astrophys. 203, 226–232 (1988)

ASTRONOMY
AND
ASTROPHYSICS

Brackett γ observations and extinction in giant H II regions in M 101

E.D. Skillman[1] **and F.P. Israel**[2]

[1] Netherlands Foundation for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, The Netherlands
[2] Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands

Received December 17, 1987; accepted February 24, 1988

Summary. We have conducted Brackett γ (Br γ) spectrophotometry of four giant H II regions in M 101. The Br γ fluxes have been compared with previously measured Hα, Hβ, and 5 GHz radio continuum fluxes in order to assess reddening and extinction. We find that the extinctions derived from comparing recombination line fluxes are always less than the extinctions derived from comparing recombination line fluxes to radio continuum fluxes, confirming previous observations of this effect. In addition, we find that the derived extinction increases with increasing comparison wavelength (using Hβ as a baseline), but the sample of H II regions measured here is too small to be conclusive on this effect. Br γ fluxes may be used to investigate the wavelength dependence of the albedo of the dust for measuring extinction. Our tentative conclusion is that this effect is not very important. The relevance of dust and extinction for the σ-L relationship for giant extragalactic H II regions is discussed.

Key words: interstellar medium: dust – extinction – H II regions – infrared radiation

1. Introduction

Understanding the dust distribution and extinction in extragalactic H II regions is important for a wide range of problems, e.g. the optical properties of the dust (Mathis, 1983; Caplan and Deharveng, 1986); the effect of internal dust on the ionizing and emitted spectrum (Sarazin, 1976; Mathis 1986); the origin of the infrared excess (Ungerer and Viallefond, 1987); and the relationship of the dust to gas ratio with abundance (Viallefond et al., 1982; Viallefond and Goss, 1986). More generally, since these H II regions are used in a wide range of applications to astrophysical problems (e.g. the distance scale, abundance studies), it is important to understand all aspects of their physical structure.

In the past, extinction in extragalactic H II regions has been studied by measuring radio continuum fluxes and Balmer line fluxes (Israel and Kennicutt, 1980; Viallefond and Goss, 1986; Caplan and Deharveng 1986; and references therein). In these studies, extinction is measured in two different ways. Comparing the radio continuum flux to the flux of a single Balmer line yields one extinction measure, and comparing the ratios of two or more Balmer lines yields a second extinction measure. In all studies to date, the extinction measured in the radio-optical comparison is greater than that from the purely optical measurement. The ratio of the two different values of extinction can be a function of the dust/H II region geometry or the optical properties of the dust grains (see Caplan and Deharveng, 1986 for further discussion). Thus, a comparison of these two extinction measures will not lead to a unique model of the dust distribution.

In principle, other hydrogen recombination lines can be used to provide additional data for measuring the extinction. Mathis (1983) discussed the use of the Hγ line, but concluded this was not very useful as the small wavelength separation from Hβ and the relative weakness of the line required an extreme measurement accuracy. In addition, the underlying stellar absorption at Hγ can be a significant fraction of the emission line strength. We present here a first attempt to use Brackett γ (Br γ) line measurements to investigate the extinction in giant extragalactic H II regions. We have chosen to observe the giant H II regions in M 101 because they are amongst the brightest known extragalactic H II regions, there are pre-existing, high quality Hα, Hβ, and radio continuum data, and the galactic reddening at the position of M 101 can be assumed to be negligible (Sandage, 1973, Sandage and Tammann, 1974).

In Sect. 2 we present new infrared and optical spectra of four giant H II regions in M 101, compare these data with data from the literature, and derive new extinction measurements. In Sect. 3 we discuss the implications of our new observations, and investigate the use of Br γ observations to help solve ambiguities previously encountered in modeling dust distributions. We also discuss the effect of extinction on the study of the σ-L relationship for giant extragalactic H II regions. In Sect. 4 we summarize our conclusions and make suggestions for further work.

2. The observations and data reduction

2.1. Brackett γ observations

Observations were carried out using the U.K.I.R.T. on Mauna Kea on the nights of 5–7 April, 1987. The observing parameters are shown in Table 1. The choice of detector was determined by the fact that the CVF was the only detector with an aperture large enough (20″) to include an entire giant H II region. In fact, in some cases, even this aperture was too small, as will be discussed later. We chose to observe the brightest regions which were compact enough that most of the flux would fall within the 20″ aperture. The spectra for the four regions observed,

---

Send offprint requests to: E.D. Skillman

Table 1. UKIRT observational parameters

Observing dates	5–7 April 1987
Telescope	UKIRT
Detector	CVF-9
Resolution	1/3
Chop	90″ N-S
Integration	10s
Spectral points	22

NGC 5461, NGC 5455, NGC 5447, and NGC 5471, are shown in Fig. 1. These regions are listed in order of increasing galactocentric radius and decreasing oxygen abundance. The oxygen abundances are approximately 0.8, 0.6, 0.4, and 0.3 of that observed in Orion, respectively (Shields and Searle, 1978; Rayo et al., 1982; Sedwick and Aller, 1981; Skillman, 1985). The oxygen abundance in Orion is about 50% of the solar value (Pagel and Edmunds, 1981).

The raw spectra were converted to a flux scale using observations of the U.K.I.R.T. standard star BS 4550 (spectral type = g III, K magnitude = 4.39) and an assumed black-body temperature of 5200 K. The resulting continuum and line fluxes are shown in Table 2. Note that the equivalent widths in all cases are well below 54 nm, which is the value expected for an ionized gas at $T_e = 10^4$ K (Wynn-Williams et al., 1978). This indicates a sizable contribution of stellar emission to the 2.2 μm continuum.

2.2. *Balmer line spectrophotometry*

Skillman (1985) has reported optical spectrophotometry of NGC 5471 using a 22″ circular aperture with the IRS on the 0.9 m telescope at Kitt Peak. In addition to the 32 min observation of NGC 5471, 16 min observations of NGC 5461 and NGC 5455 were also conducted with the same instrument on the same night. The IRS was configured for a wavelength range of 3600–7000 Å with a resolution of 13 Å (FWHM). The observations were bracketed by 8 min observations of the standard stars HZ 44 and BD +33°2642. The relative flux distributions for the standard stars agreed to within a few percent. The absolute flux calibrations of the standard stars agreed to within 5%.

After these observations were obtained, Hayes and Massey (1984) reported that the IRS suffered from an instrumental defect which scattered 8% of the light from the object aperture to the sky aperture, at a highly degraded resolution. Thus, emission line flux measurements were potentially affected. Inspection of our

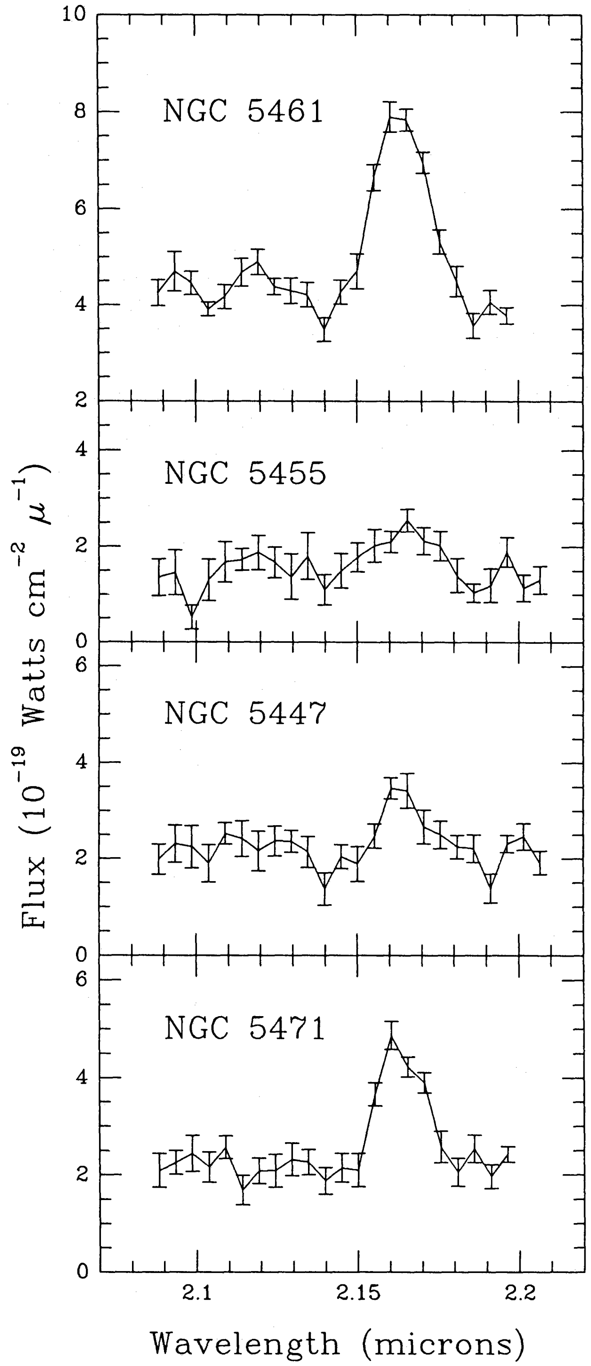

Fig. 1. Infrared spectra in the region of Brackett γ for four giant H II regions in M 101

Table 2. Br γ measurements

Object	Continuum at 2.17 μm (10^{-19} W cm^{-2} μm^{-1})	Br γ flux (10^{-20} W cm^{-2})	Br γ EW (nm)
NGC 5461	4.0	0.73 ± 0.02	15
NGC 5455	1.4	0.21 ± 0.06	21
NGC 5447	2.1	0.26 ± 0.07	19
NGC 5471	2.2	0.46 ± 0.08	12

original data revealed features in the sky spectrum of less than 1% of the peak in the corresponding emission line in the object spectrum and with a FWHM of about 60 Å. In order to minimize the, albeit small, effects of this defect, the spectra were analyzed in the following way: Fluxes were not measured by fitting gaussian profiles to the emission lines as in Skillman (1985). Instead, the emission lines were summed over the central 6 pixels (between roughly 0.4 power points), and a continuum level was fixed by interpolating over regions at least 100 Å away from the line. Via this method, reliable relative fluxes could be obtained from the data. (An additional benefit of this technique is that the Hα line strengths are free of contamination from the [N II] lines.)

In order to obtain absolute fluxes, an estimate of the instrumental profile was made, in addition to a correction for the subtraction of the scattered line emission in the sky aperture (3.4%). The line fluxes were then corrected for underlying stellar absorption (1.5 Å EW for NGC 5461 and 2 Å EW for NGC 5455 and NGC 5471). The derived absolute fluxes for Hα and Hβ, and the relative fluxes for all four measured Balmer lines are listed in Table 3. The logarithmic reddening correction at Hβ, c(Hβ), was determined for each line pair assuming the intrinsic line ratios of Brocklehurst (1971) and the reddening law of Whitford (1958). These data are also listed in Table 3.

Table 3. Balmer line flux and reddening measurements

	Hα	Hβ	Hγ	Hδ
NGC 5461				
Flux (10^{-20} W cm^{-2})	31.3	6.9		
Relative Flux	4.49	1.00	0.39	0.21
c(Hβ)	0.57	...	0.54	0.41
NGC 5455				
Flux (10^{-20} W cm^{-2})	17.5	5.6		
Relative flux	3.13	1.00	0.45	0.24
c(Hβ)	0.12	...	0.16	0.17
NGC 5471				
Flux (10^{-20} W cm^{-2})	35.4	12.8		
Relative flux	2.78	1.00	0.46	0.25
c(Hβ)	0.01	...	0.07	0.09

2.3. *Comparison with data from the literature*

In Table 4a we have listed previously published Hβ photometry ($H\beta_M$; Melnick et al., 1987), Hα photometry ($H\alpha_K$; Kennicutt 1978), and 5 GHz radio continuum measurements (S_5) (Israel et al., 1975; Sramek and Weedman, 1986). We have also tried to estimate the Hβ fluxes from the multi-aperture photometry (compiled from the literature) of Rosa (1983)($H\beta_R$) by interpolating to value for a 20″ aperture. For the radio continuum measurements, we have listed both an estimated core component flux and a total flux. From these two measurements we can calculate a minimum and a maximum reddening derived by comparing the radio continuum and Hβ measurements. For NGC 5461, NGC 5455, and NGC 5471 we have adopted the total 5 GHz fluxes from the high resolution observations of Sramek and Weedman (1986) as the core fluxes. The total fluxes are from Israel et al. (1975).

In Table 4b we list a comparison of the IRS spectrophotometry with the published optical data. The first column shows the ratio of our Hβ fluxes to those of Melnick et al. (1987), the second a comparison of our data with those from Rosa (1983), and the third column compares our Hα fluxes to those of Kennicutt (1978). We would expect that our flux measurements should be somewhat smaller than those of Melnick et al. and Kennicutt because the 22″ aperture of the IRS does not cover the complete extent of the H II regions observed. We find this is true in most cases. Our measurements are more consistent with the photometry of Kennicutt, but aperture size effects may affect the comparison. The agreement of our Hβ values with those derived from Rosa (1983) is not bad, especially considering the heterogeneous nature his data base and the uncertainty in interpolating to our aperture. The fourth column compares our values of c(Hβ) derived from the Hα/Hβ ratio with values obtained by Kennicutt (private communication) with moderate and large aperture spectrophotometry (9″ and 12″ apertures for NGC 5461, NGC 5455, NGC 5447, and 20″ aperture for NGC 5471). Although the c(Hβ) values are similar in showing a trend of decreasing reddening

Table 4
A) Fluxes derived from the literature

	$H\beta_M$ (10^{-20} W cm^{-2})	$H\beta_R$ (10^{-20} W cm^{-2})	$H\alpha_K$ (10^{-20} W cm^{-2})	S_5 (core) (mJy)	S_5 (total) (mJy)
NGC 5461	10.3	6.5	34.7	11	22
NGC 5455	7.0	4.7	20.0	2.5	5.5
NGC 5447	6.8	...	...	5	10
NGC 5471	12.4	12.0	38.9	8	12

B) Comparison of observations

	$H\beta/H\beta_M$	$H\beta/H\beta_R$	$H\alpha/H\alpha_K$	$c(H\beta)/c(H\beta)_K$
NGC 5461	0.67	1.06	0.90	0.57/0.50
NGC 5455	0.80	1.19	0.88	0.12/0.36
NGC 5447	...	...	...	.../0.44
NGC 5471	1.03	1.07	0.92	0.01/0.23

Table 5. Derived values of C(Hβ)

	Hα/Hβ	Brγ/Hβ	S_5/Hβ (min)	S_5/Hβ (max)
NGC 5461	0.57	0.62	0.74	1.04
NGC 5455	0.12	0.15	0.16	0.51
NGC 5447	(0.44)	(0.16)	(0.36)	(0.66)
NGC 5471	0.01	0.17	0.25	0.43

with decreasing nebular abundance, there is a scatter in the point-by-point comparison at the level of 0.1 in c(Hβ).

2.4. *Comparison of derived extinctions*

In Table 5 we have listed the values of c(Hβ) derived from a comparison of the fluxes measured at the different wavelengths. The first column shows values of c(Hβ) derived from the Hα/Hβ ratios of our IRS spectrophotometry. The second column shows the extinction derived from comparing our Brγ fluxes with the Hβ fluxes from the IRS observations. The third and fourth columns show the values of c(Hβ) derived from comparing the radio flux measurements with the Hβ fluxes from the IRS measurements. For the derivation of these extinctions we have used the theoretical calculations of Brocklehurst (1971) and Giles (1977) for the Balmer and Brackett line ratios, the formula of Scheuer (1960) and Oster (1961a,b) as parameterized by Caplan and Deharveng (1986) for the comparison of Hβ and radio fluxes, and the galactic reddening law parameters of Howarth (1983). We have assumed electron temperatures of 9000 K for NGC 5461, 10,000 K for NGC 5455, 11000 K for NGC 5447, and 13,000 K for NGC 5471 (Rayo et al., 1982; Sedwick and Aller, 1981; Skillman, 1985). For NGC 5447 we have shown the value of c(Hβ) from Hα/Hβ from Kennicutt's moderate aperture spectrophotometry. For the values of c(Hβ) from Brγ/Hβ and S_5/Hβ we have used Melnick's value of the Hβ flux for NGC 5447. Thus these values are enclosed in parentheses.

Before we continue on to the interpretation of the results in Table 5, we wish to discuss some of the uncertainties involved. Although we take comfort in the consistency between our Hα fluxes and those of Kennicutt, we are also disturbed by the discrepancies between our Hβ fluxes and those of Melnick et al. It is concluded that there can be large systematic differences in flux measurements between authors, and extinctions derived from comparing fluxes from two different data bases may be subject to large errors. Because of this, the values for NGC 5447 are deemed unreliable and will not be discussed further. In addition, the comparison of our optical spectrophotometry with that of Kennicutt indicates that errors in c(Hβ) must be of order 0.1.

By nearly matching the aperture sizes of the optical and infrared measurements, we have tried, as much as possible, to constrain any effects of aperture size. However, we could not do this for the radio observations, and therefore there exists some uncertainty in the optical-radio comparison. In all cases, the 22″ aperture was at least a factor of 2 times larger than the core diameters as measured from Hα plates (Sandage and Tammann, 1974), but ranged from 70% to 90% of the halo diameters. Although the distribution of flux between core and envelope components can show large variations from region to region, using Hα and λ6 cm observations as a guide, we chose only regions in which we expected to detect 90% of the total flux using the 22″ aperture. Two regions are most liable to aperture effects. These are NGC 5447, because it shows no strong core component, and NGC 5461, because it has a relatively large envelope (40″) from which 40% of the radio continuum arises (Israel et al., 1972).

3. Interpretation

3.1. *A discussion of the derived extinctions*

The derived extinctions listed in Table 5 can be viewed in two different ways. On the one hand, the derived extinctions show a trend of increasing extinction at Hβ with increasing value of the comparison wavelength used. The extinctions at Hβ derived through Brackett γ observations are more than those derived from Hα observations and less than those derived from the radio continuum. On the other hand, the differences are small, especially when considering the errors inherent in the measurements.

In order to better assess these data, we have constructed a plot showing the values for the three most reliable regions. Figure 2 shows values of c(Hβ) derived from comparing the radio free-free emission with the Hβ emission versus the values of c(Hβ) derived from comparing recombination lines fluxes. Each nebula is shown as a point with error bars. The vertical error bars show the difference between using the total radio continuum flux (maximum c(Hβ)) and the core component of the radio continuum (minimum c(Hβ)). The horizontal error bars show the difference between the value of c(Hβ) derived from the Hα/Hβ ratio (minimum c(Hβ)) and the Brγ/Hβ ratio (maximum c(Hβ)).

All 3 points lie above the line labeled "uniform interstellar dust", which corresponds to agreement between the different methods of measuring extinction. Thus, the 3 points in Fig. 2 to some extent support the conclusion of Israel and Kennicutt (1980) that there is significant absorption in giant extragalactic H II regions that cannot be accounted for on the basis of the observed Balmer decrement. Skillman (1984) suggested that much of this "excess" absorption may be accounted for by beam size effects, and this also appears to be true here, as the average discrepancy between the radio-optical and the Balmer decrement measures of the reddening is much less for the present observations than the average observed by Israel and Kennicutt (1980).

In order to compare our present extinction values with those derived by Israel and Kennicutt (1980), we have included their data for the same three nebulae in Fig. 2 (open triangles). Since their values were reported as A_V, the extinction at a wavelength of 5550 Å, we have used the reddening curve of Howarth (1983) to convert values of A_V to c(Hβ) ($c(\mathrm{H}\beta) = A_V/2.1$). Note the large difference in the values of c(Hβ) (ff-rec) for the two data sets. Since our maximum values use the same radio continuum data, and, since there is relatively good agreement between our Hα fluxes and those of Kennicutt (1978), one might expect the tops of the vertical error bars to coincide with the values of Israel and Kennicutt (except for the small differences due to using better temperature estimates and the slightly smaller Balmer line fluxes). In fact, for NGC 5471 and NGC 5455, the differences in c(Hβ) (ff-rec) are large.

These large differences demonstrate the danger in assuming a standard reddening law when deriving extinction. As pointed out by Caplan and Deharveng (1986), this leads to a "fictitious" extinction. The values derived by Israel and Kennicutt came from a comparison of Hα and radio continuum fluxes. Thus they have measured the extinction at Hα. When one assumes a standard

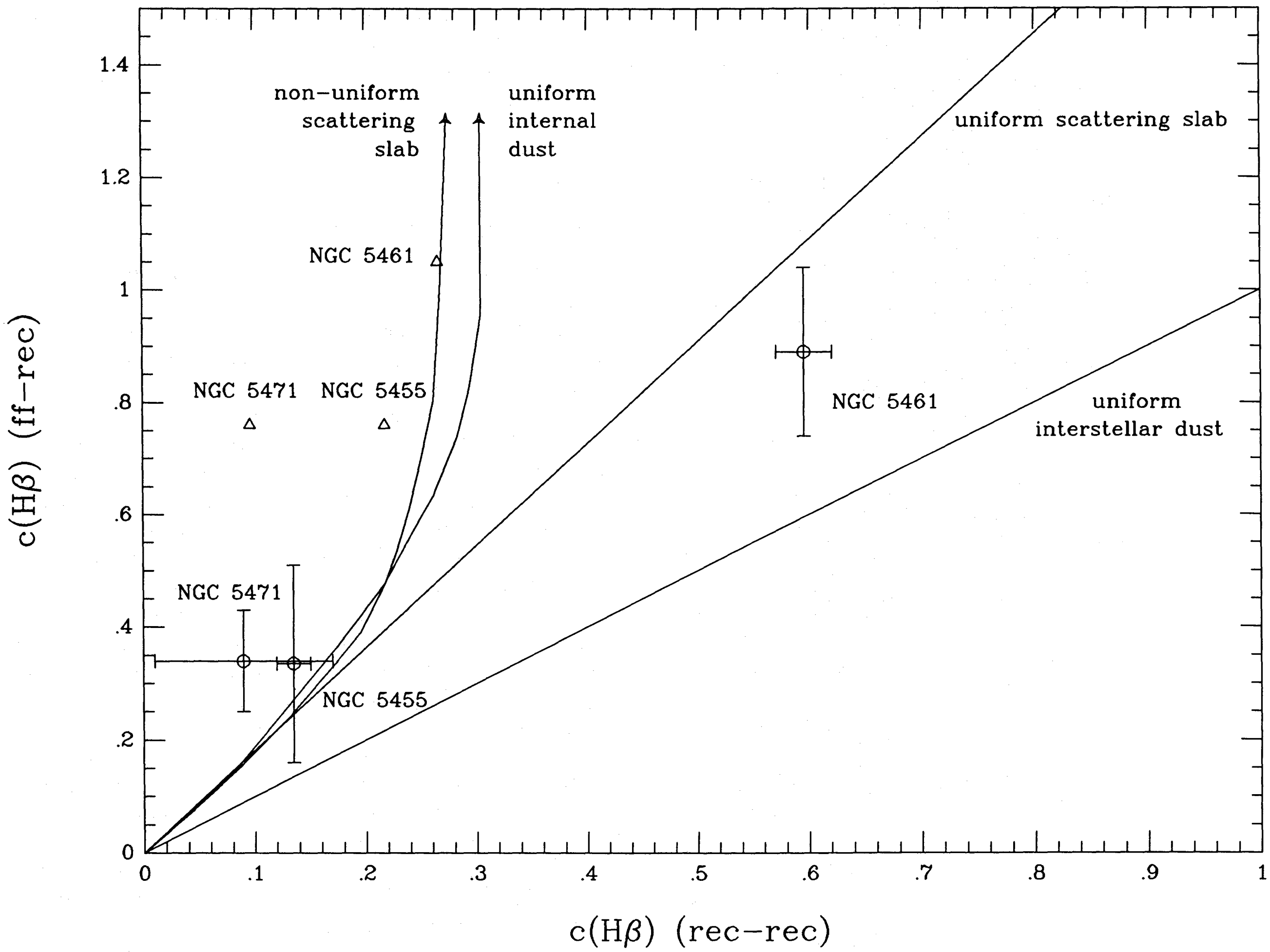

Fig. 2. Plot of extinction at Hβ derived from comparing the radio continuum flux (free-free emission) with the Hβ flux (recombination) versus the extinction at Hβ derived from recombination line ratios (Hα/Hβ and Brγ/Hβ). The new data from this paper are shown as points with error bars (described in the text). The open triangles show data from the paper of Israel and Kennicutt (1980). The straight line labeled "uniform interstellar dust", with a slope of 1, indicates agreement. The other three lines show results of model calculations from Mathis (1983), also described in the text

reddening law to derive the extinction at a smaller wavelength (e.g. A_V or $c(\mathrm{H}\beta)$), one *amplifies* the effect, predicting an excessive extinction at the shorter wavelength. Using our data to derive extinctions at Hα, we obtain values in reasonable agreement with those of Israel and Kennicutt (as must be the case). We therefore conclude that by measuring the extinction at Hα, but reporting it as a visual extinction, A_V, Israel and Kennicutt exaggerated the excess absorption that they discovered. The exaggeration amounts to the difference between assuming grey absorption (i.e. no color dependence) and assuming a galactic reddening law. Since, in the standard galactic reddening law, $A_V = 1.25A_\alpha$ (Caplan and Deharveng, 1986), the extinction reported by Israel and Kennicutt (1980) may be exaggerated by as much as 25%.

Despite the fact that the amplitude of the excess absorption may have been overestimated by Israel and Kennicutt, it remains a real effect. The source of this "excess" absorption has been discussed by several authors (Israel and Kennicutt, 1980; Viallefond and Goss, 1986; Caplan and Deharveng, 1986; and references therein). There is no unambiguous method for distinguishing between internal dust (clumpy or uniform) and clumpy foreground dust. Skillman (1985) has noted that for the simplified case of a spherical, uniform density H II region, the two cases can be distinguished. Internal reddening should correlate with surface brightness, whereas foreground reddening should show no correlation with H II region surface brightness. Skillman (1985) found evidence for both types of extinction in a detailed study of NGC 5471. Viallefond et al. (1982) arrived at a similar conclusion in a study of NGC 595 in M 33. Viallefond (private communication) also finds a striking correlation of reddening with surface brightness in NGC 604. In a study of tens of H II regions in M 33, Viallefond and Goss (1986) find that the extinctions derived for entire H II regions are systematically less than those derived for the cores of the regions and argue that this implies a large amount of extinction internal to the regions. From a study of the H II regions in the Large Magellanic Cloud, Caplan and Deharveng (1986) conclude that most of the "excess" extinction must arise close to or within the H II regions. From a study of the H II regions in M 51, van der Hulst et al. (1988) found that by carefully matching the spatial resolution and apertures used in radio and optical studies, the difference between radio-optical and optically derived extinctions is always less than 0.6 mag, and in some cases, nonexistant.

As more evidence collects, it appears that there is generally a discrepancy between the total extinction and that derived from the Balmer decrement (although the difference, on average, is probably smaller than that found by Israel and Kennicutt), and that most of this difference is attributable to dust associated with the H II region. This conclusion, however, still leaves open the question whether the observed dust is uniformly mixed with the ionized gas or exists in the form of opaque clumps.

What then, can new observations at Brackett γ tell us? In Fig. 2 we have also included results of model calculations by Mathis (1983) comparing radio-optical extinctions with $H\alpha/H\beta$ extinctions. The straight line labeled "uniform scattering slab" shows the effect of modeling the dust with a different albedo (ω) at $H\alpha$ ($\omega = 0.54$) than at $H\beta$ ($\omega = 0.63$). (In all three of the models of Mathis shown we have used his "$\alpha 1$" parameters for the dust based on the Mathis et al. (1977) model dust mixture and the White (1979) model of dust properties.) The two curved lines, which trace nearly identical paths, are the result of two different dust geometries; one with dust mixed with the gas uniformly in a spherical nebula, and one with a foreground scattering slab of varying optical depth. Caplan and Deharveng (1986) also show model calculations where different assumptions of the dust geometry give rise to different tracks in the extinction-extinction plane. The salient point is that very different dust distributions can produce identical positions in the extinction-extinction plane.

However, by adding $Br\gamma$ observations it may be possible to test the importance of the variation of albedo of the dust with wavelength. In White's (1979) model, the albedo is falling rapidly at wavelengths larger than $H\alpha$. Although White's calculations stop at $\lambda = 1\,\mu$, where $\omega = 0.45$, it is reasonable to assume that $\omega(Br\gamma)$ lies in the range of 0.3 to 0.4. Since most of the effect of scattering in Mathis' model depends on the albedo difference, and since the estimated albedo difference between $Br\gamma$ and $H\alpha$ is greater than that between $H\alpha$ and $H\beta$, it is plausible that $Br\gamma$ observations can put constraints on the importance of the effect that Mathis has drawn attention to. Certainly model calculations at the wavelength of $Br\gamma$ are desirable.

Mathis (1983) has argued that small differences in albedo produce large differences in the measured extinction. Comparing extinctions from $H\alpha/H\beta$ ratios with those of $Br\gamma/H\beta$, where we predict a very large difference in albedo, we see a very small difference in measured extinction. Nonetheless, this is not conclusive. The increase in albedo difference would increase the extinction discrepancy, moving an individual point to the left in Fig. 2. On the other hand, by choosing a longer wavelength, the total extinction is decreased, moving a point to the right in Fig. 2. Thus the two effects may compensate one another. At this time, the fact that the differences are small in all three cases argues that scattering is not that important. However, in light of the lack of appropriate model calculations, and considering the errors in the data relative to the size of the effect, and the small sample studied, this conclusion must be regarded as speculative. We would prefer to stress the potential importance of the method and not the tentative conclusion. With the recent appearance of infrared array detectors, we might hope to significantly improve on the quality of $Br\gamma$ observations. A carefully planned series of observations at optical, infrared, and radio wavelengths could achieve much smaller observational uncertainties compared to those encountered in this study. It would be especially interesting to compare images at $H\beta$, $H\alpha$, $Br\gamma$, and 5 GHz to study the spatial variation of the derived extinctions.

3.2. Extinction and the σ-L relationship

Recent studies by Roy et al. (1986), Hippelein (1986), and Melnick et al. (1987), have firmly established the reality of the correlation of line width and luminosity (the σ-L relation) in giant extragalactic H II regions first discovered by Melnick (1978). Currently there are two outstanding problems concerning the σ-L relationship: 1.) It is not clear what the underlying physical mechanism is (Skillman and Balick, 1984; Hippelein, 1986; Melnick et al., 1987); and 2.) There is a significant scatter in the observed data. If one intends to use the σ-L relationship as a distance indicator, then the large scatter in the relationship is naturally disturbing (Melnick, 1979). This scatter could be due to either inherent properties of the H II regions or observational uncertainties. Comparison of line width measurements by various authors indicate that these measurements are reliable (repeatable, low dependence on aperture size). However, luminosity estimates for giant extragalactic H II regions are suspect for a number of reasons. As emphasized by Melnick et al. (1987), care must be taken in matching the size of the aperture to the region, and in properly subtracting contamination from the host galaxy. In addition, as discussed in this paper, the reddening correction is uncertain. Usually $H\beta$ flux measurements are dereddened using reddening corrections based on the Balmer decrements obtained with small aperture spectrophotometry. This can result in a very large error in determining the $H\beta$ luminosities.

We can now ask, can the extinction correction be a significant source of the scatter in the σ-L relationship? Melnick et al. (1987) note that the scatter in the σ-L relationship decreases significantly when they correct for the extinction derived from the Balmer decrement. Since the separate effects of galactic and extragalactic extinction have not been studied for their sample, one would predict an improvement, just by removing galactic extinction. However, the contribution of extinction local to the nebula may not be correctly accounted for.

To investigate the affect of extinction corrections on the scatter in the σ-L relationship, it should be possible to compare σ-L diagrams where the luminosity is measured at different wavelengths. Hippelein (1986) has discussed the σ-L relationship using 5 GHz radio continuum fluxes instead of Balmer line fluxes. He finds an increase of about 20% in the slope in the $\log(\sigma) - \log L$ diagram, and attributes this to larger H II regions having more internal dust. In repeating this exercise, we find no difference in the correlation coefficient for the two relationships. This would argue that whereas extinction corrections affect the slope of the relationship, they do not appreciably affect the scatter. More high quality radio continuum measurements are needed to pursue this question. In the meantime, since the derived slope is wavelength dependent, and since the radio continuum measurements are free from reddening corrections (although may occasionally suffer from contamination by nonthermal emission, see e.g. Skillman, 1985), studies addressing the physical nature of the σ-L relationship should accept the larger value for the slope.

An underestimate of the total extinction, if unaccounted for, should also have another systematic effect on the σ-L relationship in the sense that regions of higher dust content (higher abundance) should show systematically lower luminosities. In fact this trend is seen (Trelevich and Melnick, 1981; Melnick et al., 1987). Since this trend has been interpreted as evidence for an abundance dependent IMF (Terlevich and Melnick, 1981), it would be worthwhile at this point to investigate further the effects of reddening corrections on the σ-L relationship.

4. Conclusions

We have compared Hβ, Hα, Br γ, and radio continuum flux measurements of giant H II regions in M101 to derive measurements of extinction. Our new observations are in agreement with the conclusion of Caplan and Deharveng (1986) that the extinction measured from the ratio of radio continuum flux to Balmer line flux is larger than that measured by comparing recombination line fluxes, but that Israel and Kennicutt (1980) have overestimated the discrepancy. We also detect a trend of the derived extinctions to increase with increasing wavelength separation. The small difference between the extinctions measured from the Hα/Hβ ratio and the Br γ/Hβ ratio implies that the wavelength dependence of the albedo of the dust may not be an important cause of the discrepant extinction measures. It is stressed that the number of H II regions observed here is small, and that new observations at optical, infrared, and radio wavelengths can lead to a better understanding of the dust distribution in the environment of giant extragalactic H II regions.

Acknowledgements. We would like to thank G. Wright for assistance with the observations, and K. Krisciunas for help with the data reductions. We are also grateful to R. Kennicutt, J. Melnick, R. Terlevich, and J.M. van der Hulst for comments on earlier versions of this paper. In addition, we wish to thank R. Kennicutt for making available unpublished data. We thank the referee for helpful comments. The United Kingdom Infrared Telescope (U.K.I.R.T.) is operated by the Royal Observatory Edinburgh on behalf of the U.K. Science and Engineering Research Council. Kitt Peak National Observatory is operated by Associated Universities for Research in Astronomy Inc., under contract with the National Science Foundation (USA).

References

Brocklehurst, M.: 1971, *Monthly Notices Roy. Astron. Soc.* **153**, 471
Caplan, J., Deharveng, L.: 1986, *Astron. Astrophys.* **155**, 297
Giles, K.: 1977, *Monthly Notices Roy. Astron. Soc.* **180**, 57p
Hayes, D., Massey, P.: 1984, KPNO Newsletter No. 33, p. 7
Hippelein, H.H.: 1986, *Astron. Astrophys.* **160**, 374
Howarth, I.D.: 1983, *Monthly Notices Roy. Astron. Soc.* **203**, 301
Hulst, J.M. van der, Kennicutt, R.C., Crane, P.C., Rots, A.H.: 1988, *Astron. Astrophys.* **195**, 38
Israel, F.P., Goss, W.M., Allen, R.J.: 1975, *Astron. Astrophys.* **40**, 421
Israel, F.P., Kennicutt, R.C.: 1980, *Astrophys. Letters* **21**, 1
Kennicutt, R.C.: 1978, Ph.D. thesis, University of Washington
Mathis, J.S.: 1983, *Astrophys. J.* **267**, 119
Mathis, J.S.: 1986, *Publ. Astron. Soc. Pacific* **98**, 995
Mathis, J.S., Rumpl, W., Nordsieck, K.H.: 1977, *Astrophys. J.* **217**, 425
Melnick, J.: 1978, *Astron. Astrophys.* **70**, 157
Melnick, J.: 1979, *Astrophys. J.* **228**, 112
Melnick, J., Moles, M., Terlevich, R., Garcia-Pelayo, J.M.: 1987, *Monthly Notices Roy. Astron. Soc.* **226**, 849
Oster, L.: 1961a, *Rev. Mod. Phys.* **33**, 535
Oster, L.: 1961b, *Astrophys. J.* **134**, 1010
Pagel, B.E.J., Edmunds, M.G.: 1981, *Ann. Rev. Astron. Astrophys.* **19**, 77
Rayo, J.F., Peimbert, M., Torres-Peimbert, S.: 1982, *Astrophys. J.* **255**, 1
Rosa, M.: 1983, ESO Workshop on Primordial Helium, eds. P.A., Shaver, D. Kunth, K. Kjar, ESO, Garching, p. 317
Roy, J.R., Arsenault, R., Joncas, G.: 1986, *Astrophys. J.* **300**, 624
Sandage, A.: 1973, *Astrophys. J.* **183**, 711
Sandage, A., Tammann, G.A.: 1974, *Astrophys. J.* **194**, 223
Sarazin, C.L.: 1976, *Astrophys. J.* **208**, 323
Scheuer, P.A.G.: 1960, *Monthly Notices Roy. Astron. Soc.* **120**, 231
Sedwick, K.E., Aller, L.H.: 1981, *Proc. Nat. Acad. Sci. USA* **78**, 1994
Shields, G.A., Searle, L.: 1978, *Astrophys. J.* **222**, 821
Skillman, E.D., Balick, B.: 1984, *Astrophys. J.* **280**, 580
Skillman, E.D.: 1984, Ph. D. thesis, University of Washington
Skillman, E.D.: 1985, *Astrophys. J.* **290**, 449
Sramek, R.A., Weedman, D.W.: 1986, *Astrophys. J.* **302**, 640
Terlevich, R., Melnick, J.: 1981, *Monthly Notices Roy. Astron. Soc.* **195**, 839
Ungerer, V., Viallefond, F.: 1987, in *Star Formation in Galaxies*, ed. C.J. Lonsdale Persson, NASA Publ. No. 2466, p. 247
Viallefond, F., Donas, J., Goss, W.M.: 1983, *Astron. Astrophys.* **119**, 185
Viallefond, F., Goss, W.M.: 1986, *Astron. Astrophys.* **154**, 357
Viallefond, F., Goss, W.M., Allen, R.J.: 1982, *Astron. Astrophys.* **115**, 373
White, R.L.: 1979, *Astrophys. J.* **229**, 954
Whitford, A.E.: 1958, *Astron. J.* **63**, 210
Wynn-Williams, C.G., Becklin, E.E., Matthews, K., Neugebauer, G.: 1978, *Monthly Notices Roy. Astron. Soc.* **183**, 237