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OBSERVATIONS OF INFRARED HYDROGEN RECOMBINATION LINE EMISSION FROM EXTERNAL GALAXIES

S. C. BECK[1,2] AND S. BECKWITH[1,2,3]
Department of Astronomy, Cornell University
AND
IAN GATLEY
United Kingdom Infrared Telescope
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ABSTRACT

Observations of infrared hydrogen recombination line emission are presented for several positions within the galaxies NGC 1068, NGC 1097, NGC 2903, and NGC 4151. Emission is seen from the arms and nuclei of these spiral galaxies. The luminosity from the most recent burst of star formation is deduced and compared to the infrared luminosity which accounts for the bulk of the total energy. Young stars (primarily O and B stars) provide most of the luminosity in the arms and nuclei of the normal galaxies NGC 1097 and NGC 2903. The infrared luminosities of the nuclei in the Seyfert galaxies NGC 1068 and NGC 4151 exceed those provided by young stars by factors of approximately 10.

Subject headings: galaxies: nuclei — infrared: spectra — interstellar: matter

I. INTRODUCTION

Many galaxies are strong sources of infrared continuum emission at wavelengths from 2 to 200 μm, and a few emit most of their luminosity at wavelengths longer than 10 μm (Rieke and Lebofsky 1978). In normal galaxies and in type 2 Seyfert galaxies, the infrared radiation is probably thermal emission from dust. It is likely that a large fraction of the infrared luminosity is provided by newly formed stars, particularly O and B stars, but the relative contribution of star formation to the total luminosity is uncertain, since the dust could be heated by a variety of different luminosity sources.

Regions of star formation in the Galaxy are typically strong sources of hydrogen recombination line and thermal radio emission produced by the H II regions created by the most massive stars. It should therefore be possible to trace regions of star formation in other galaxies by mapping the hydrogen recombination lines. By using infrared lines, the effects of extinction by dust can be minimized. In principle the radio continuum emission can also trace star-forming regions, but in practice the continuum emission is often badly contaminated by nonthermal radiation.

This paper presents preliminary measurements of the Brα(($n = 5$–4) and Brγ($n = 7$–4) lines of hydrogen in several spiral galaxies. Observations have been made both toward galactic nuclei and in the direction of the spiral arms. From the line fluxes, the total luminosity from massive young stars can be estimated and compared to the total luminosity. In this way, the fraction of the luminosity provided by young stars is assessed in different galaxies and between different parts of each galaxy.

II. OBSERVATIONS

The observations were made with the cooled grating spectrometer described by Beckwith *et al.* (1983) on the United Kingdom Infrared Telescope (UKIRT) and the Infrared Telescope Facility (IRTF) at Mauna Kea during 1981 November and 1982 February. The results are given in Table 1. The entrance diaphragm was between 4″ and 8″ in diameter as indicated in Table 1; the instrumental resolving power was approximately 800 ($\lambda/\Delta\lambda$) for all observations. Sky subtraction was accomplished by chopping 60″ east-west. The pointing was controlled either by guiding directly on the galaxies or by offsetting from nearby SAO stars; we estimate the absolute pointing uncertainty to be $\pm 1''$.

For each spectral line, we observed at least seven wavelengths, spaced by one-half the spectral resolution and centered on the line. Observations of the hydrogen recombination lines in galactic H II regions and planetary nebulae were used to calibrate the wavelength scale. The flux density scale was established by observations of standard stars. Based on the internal variations in the observations of the standard stars and the uncertainty in the flux densities of the stars at the wavelengths of the hydrogen lines, we estimate a total uncertainty in the flux density scale of 10%. A Brγ line observed from NGC 1097 is shown in Figure 1 as a sample of the data.

III. ANALYSIS

When both Brγ and Brα are measured, the interstellar reddening can be estimated from the deviation of the line flux ratio from the unreddened value predicted by recombination theory (Brα/Brγ = 2.8; Giles 1977; Brocklehurst 1971). Use of an infrared reddening curve (Becklin *et al.* 1978) gives

[1] Visiting Astronomer UKIRT.
[2] Guest Investigator, Infrared Telescope Facility, which is operated by the University of Hawaii under contract through the National Aeronautics and Space Administration.
[3] Alfred P. Sloan Foundation Fellow.

TABLE 1

RESULTS OF BRACKETT LINE OBSERVATIONS

Source[1] (1)	$F(\mathrm{Br}\gamma)$ ergs s cm^{-2} (2)	$F(\mathrm{Br}\alpha)$ ergs s cm^{-2} (3)	$A_{2.17\,\mu\mathrm{m}}$ (mag) (4)	Beam Diameter (5)	N_L (photons s^{-1}) (6)	L Total $L_\odot$ (OB star) (7)	$S_{10\,\mu\mathrm{m}}$ (Jy)[2] (8)	L Total $L_\odot$ (10 μm) (9)
NGC 2903 (nuc)	3.5(−14) ±1.2(−14)	1.4(−13) ±1.8(−14)	0.8	8″ = 330 pc	4.9(52)	2.6 (9)	0.22	1.6 (9)
NGC 2903 6″N, 4″E	not observed	<1.8(−14)						
NGC 1097 (nuc)	<1.6(−14)	not observed		4″ = 456 pc			0.065	3.7 (9)
9″E	3.6(−14) ±1. (−14)	not observed			1.9(53)	1 (10)	0.106	6 (9)
9″W	2.6(−14) ±1. (−14)	not observed			1.4(53)	7.3 (9)	0.095	5.5 (9)
3″W, 10″S	4.8(−14) ±1.5(−14)	not observed			2.5(53)	1.3(10)	0.15	8.6 (9)
NGC 1068 (nuc)	1.9(−13)[3]	not observed		4″ = 390 pc	7 (53)	3.7(10)	25	1 (12)
NGC 1068 12″W, 6″S	3.2(−14) ±1 (−14)	not observed		...	1.2(53)	6.2 (9)	0.19	7.6 (9)
NGC 4151	5.3(−14) ±1.8(−14)	8.7(−14) ±2.9(−14)	~0	8″ = 780 pc	1.2(53)	6 (9)	1.2	4.8(10)

[1] Positions used for galactic nuclei are (1950): NGC 2903 at $9^{\mathrm{hr}}29^{\mathrm{m}}20^{\mathrm{s}}.3$, +21°43′22″.5; NGC 1097 at $2^{\mathrm{hr}}44^{\mathrm{m}}11^{\mathrm{s}}.5$, −30°29′6″; NGC 1068 at $2^{\mathrm{hr}}40^{\mathrm{m}}7^{\mathrm{s}}$, −0°13′31″; and NGC 4151 at $12^{\mathrm{hr}}8^{\mathrm{m}}0^{\mathrm{s}}.7$, +39°40′.

[2] The 10 μm flux measurements of NGC 2903, NGC 4151, and NGC 1068 are from Rieke and Low (1975), NGC 1097 from Telesco and Gatley (1981), and the extranuclear 10 μm flux in NGC 1068 from Telesco *et al.* 1983.

[3] Brγ in NGC 1068 nucleus measured by Hall *et al.* 1981.

the total extinction at any wavelength from the reddening. In Table 1, the extinction computed from the Brα/Brγ ratio is given for the two positions where both lines are observed. Owing to the faintness of the targets, only one line has been observed for most positions, and we have not estimated an extinction in these cases. Fluxes and quantities derived from fluxes are therefore lower limits only.

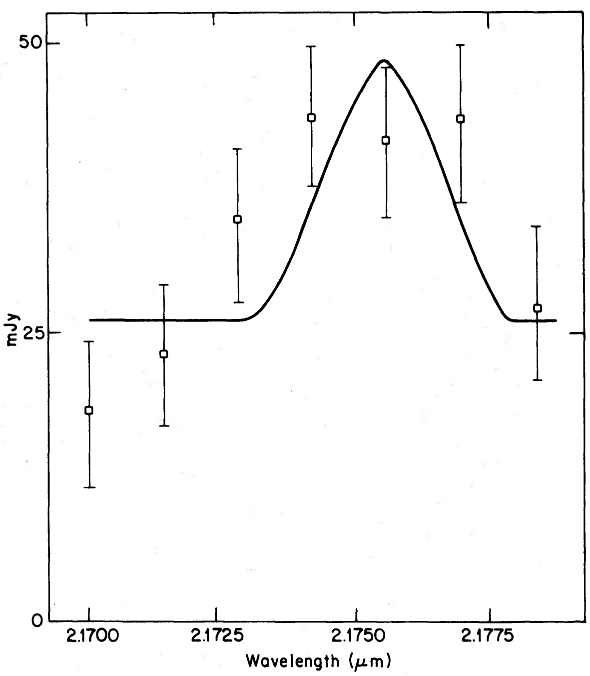

FIG. 1.—The Brγ line observed with a 4″ beam 9″ east of the nucleus of NGC 1097. The best fit to an instrumental profile is also shown. Only statistical uncertainties are shown.

For the two cases where the extinction is known, NGC 2903 and NGC 4151, the extinction is relatively small. The extinction derived for the nucleus of NGC 2903 corresponds to about 15 mag of visual obscuration, in good agreement with the 16 mag of visual extinction found by Lebofsky and Rieke (1979) from their study of the infrared continuum radiation, but ~15 times greater than that found from the visual observations of Turnrose (1976). This is not surprising since optical measurements are confined to regions of low extinction, while even rather heavily obscured regions can be observed at infrared wavelengths. If 1 mag is typical of the 2.17 μm extinction in the directions where the extinction has not been derived, then the line fluxes and quantities derived from them are underestimated by about a factor of 3. Since there is probably a distribution of extinction and H II regions along the line of sight in each position, it is likely that the Brγ line is seen only from the H II regions that suffer 1 mag or less of extinction, the others being too heavily obscured to contribute significantly to the line flux. The weakness of the Brα line in the places where it has been observed indicates that the line fluxes are probably not underestimated by as much as a factor of 10, however.

The total luminosity of newly formed stars has been derived from the Brγ line flux and is listed in column (7) of Table 1. From the observed line fluxes, one can find the rate of emission of ionizing photons for the H II regions. Recombination theory implies that one Brγ photon is emitted for every 84 Lyman continuum photons absorbed by the gas, assuming an average electron temperature of 10^4 K and an electron density of 10^4 cm^{-3} (Brocklehurst 1971; Giles 1977). From the emission rate of ionizing photons, the total luminosity can be calculated with some assumptions about the distribution of different types (masses) of ionizing stars. Assuming the stars were formed instantaneously according to the initial mass function given by Miller and Scalo (1979) and using the luminosity-mass relation given by Allen (1973) for main-sequence stars, we find the ratio of total luminosity to rate of emission of ionizing photons is between 5.3×10^{-44} $L_\odot$ photons s^{-1} and 2.8×10^{-44} $L_\odot$ photons s^{-1} if the most massive stars are between 30 and 60 $M_\odot$. This result is insensitive to the lower mass limit if it is less than 5 $M_\odot$. From the low stellar temperatures found in both galactic and extragalactic H II regions (Beck, Lacy, and Geballe 1979; Lacy, Beck, and Geballe 1982), the upper mass limit of 30 $M_\odot$ is appropriate. The total luminosity listed in Table 1 has therefore been derived as $L_T = 6 \times 10^{14} F(\mathrm{Br}\gamma) d^2(\mathrm{kpc}) L_\odot$, where L_T is the total luminosity, $F(\mathrm{Br}\gamma)$ is the Brγ flux in ergs s^{-1} cm^{-2}, and d(kpc) is the distance to the object in kpc.

The bulk of the total luminosity in galaxies is radiated at infrared wavelenths. In all our targets, the 10 μm flux density has been measured with spatial resolutions comparable to those used here (references in table). If the dust emitting at 10 μm is heated by Lyα photons, the total luminosity is approximately $(100 \pm 40)\ S_{10}\, d^2(\mathrm{kpc})\ L_\odot$, where S_{10} is the 10 μm flux density in janskys (Scoville *et al.* 1983). In Table 1, the total luminosities (L_T) derived from 10 μm measurements are shown for each position. Comparison of luminosity from young stars derived from the hydrogen lines with that derived from 10 μm measurements shows the relative importance of recent star formation as an energy source in the different positions.

The uncertainties in the derivation of total luminosity from either the hydrogen lines or the 10 μm flux density are large. The L_T derived from the 10 μm observations can vary by at least 40%, and probably more (see, e.g., Wynn-Williams and Becklin 1974), and L_{TOT} derived from the line observations is uncertain by at least a factor of 2, depending on the initial mass function and the extinction. It may be seen from Table 1, however, that in this sample of galaxies at least the two methods of determining total luminosity either agree to better than 70% or show that the luminosity from young stars is insufficient to produce the total luminosity implied by the 10 μm observations by a factor of 8 or more. Even the somewhat uncertain derivations used here are apparently sufficient to separate galaxies into those powered almost entirely by recently formed stars and those powered mainly by other luminosity sources.

IV. DISCUSSION

In the normal galaxies presented here (NGC 2903 and NGC 1097) the hydrogen line measurements show that the bulk of the total luminosity is provided by young stars and that a single recent burst of star formation is apparently sufficient to account for most of the stellar luminosity. The same can be concluded for the arm of NGC 1068, evidence that in this Seyfert galaxy the arms resemble those of a normal spiral galaxy.

In the nuclei of the Seyfert galaxies NGC 1068 and NGC 4151, the luminosity inferred from the 10 μm flux is much greater than that which can be attributed to young stars following our simple models. There are several possible causes for these discrepancies. First, observational difficulties peculiar to these galaxies (the very broad components of some lines, for example) may have led us to underestimate the hydrogen line fluxes and thus the number of young stars. Second, these galaxies may be powered by young stars, but conditions of the star burst region may be such that the models used to derive luminosities fail badly. Third, the galaxies may contain other sources of strong 10 μm emission which are not related to recent star formation.

In NGC 1068 the luminosity of young stars derived from the H I lines is a factor of 30 lower than the luminosity derived from 10 μm flux. There are two factors which may mitigate the disagreement. The extinction to the nucleus of NGC 1068 is known to be large; Lebofsky, Rieke, and Kemp (1978) find $A_{2.17\,\mu\mathrm{m}} \sim 1$ mag from continuum observations, so it seems clear that the luminosity derived from the uncorrected Brγ flux is an underestimate. Another peculiarity of NGC 1068 derived from continuum observations is that the infrared emission comes from two components which are at least in part spatially distinct: a core source of diameter $\leq 1''$ which is strong at 10 μm (Becklin *et al.* 1973) and an extended region with a diameter between 6″ and 30″ which produces most of the far-infrared flux (Telesco, Becklin, and Harper 1980; Telesco and Harper 1980). If the Brα flux observed in the southwest arm is typical of the wider region near the nucleus, the extended far-infrared emission could be powered by young stars. This agrees with Scoville, Young, and Lucy's (1983) result that the extended infrared source contains a large number of molecular clouds and recently formed stars. The nature of the core 1″ source is difficult to determine. It differs from the spectra of normal infrared sources in having excess flux at $\lambda < 30$ μm (Telesco and Harper 1980) such that the L_{TOT} derived from the 10 μm flux in our simplest model is three times the total 1–300 μm luminosity observed in the galaxy (Jones and Stein 1975). If the radiating dust is as hot as 500 K, for example, the 10 $\mu\mathrm{m}/L_{\mathrm{TOT}}$ will be quite different from that used in this analysis. However, even if it is energetically possible to power the 10 μm source with O and B stars, the small size ($\sim$90 pc diameter) of the region means that star formation, if it is responsible for most of the luminosity, may be very different from that occurring in the arms.

NGC 4151 presents special observational difficulties because of possible infrared variability (Stein, Gillett, and Merrill 1974; Rieke and Lebofsky 1981) and very broad lines. A comparison of our Brα and Brγ line fits and fluxes with those of Rieke and Lebofsky (1981) and McAlary and McLaren (1981) suggests that we have measured accurately only the narrow components of the H I lines. These results therefore imply that roughly one-tenth of the total infrared luminosity of this galaxy is due to young stars in the narrow-line emission region, consistent with the fact that NGC 4151 is known to contain a strong nonthermal source.

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REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (32 ed.; London: Athlone).
Beck, S. C., Lacy, J. H., and Geballe, T. R. 1979, *Ap. J.*, **231**, 28.
Becklin, E. E., Matthews, K., Neugebauer, G., and Wynn-Williams, G. 1973, *Ap. J.* (*Letters*), **186**, L69.
Becklin, E. E., Matthews, K., Neugebauer, V., and Willner, S. P. 1978, *Ap. J.*, **220**, 831.
Beckwith, S., Evans, N. J. II, Gatley, I., Gull, G., and Russell, R. W. 1983, *Ap. J.*, **264**, 152.
Brocklehurst, M. 1971, *M.N.R.A.S.*, **153**, 471.
Giles, K. 1977, *M.N.R.A.S.*, **180**, 57.
Hall, D. N. B., Kleinmann, S. G., Scoville, N. Z., and Ridgway, S. T. 1981, *Ap. J.*, **248**, 898.
Jones, B., and Stein, W. 1975, *Ap. J.*, **197**, 297.
Lacy, J. H., Beck, S. C., and Geballe, T. R. 1982, *Ap. J.*, **255**, 510.
Lebofsky, M. J., and Rieke, G. H. 1979, *Ap. J.*, **229**, 111.
Lebofsky, M. J., Reike, G. H., and Kemp, J. C. 1978, *Ap. J.*, **222**, 95.
McAlary, C. W., and Maclaren, R. A. 1981, *Ap. J.*, **250**, 98.
Miller, G. E., and Scalo, J. M. 1979, *Ap. J. Suppl.*, **41**, 513.
Rieke, G. H., and Lebofsky, M. J. 1978, *Ap. J.* (*Letters*), **220**, L37.
Rieke, G. H., and Lebofsky, M. J. 1981, *Ap. J.*, **250**, 87.
Rieke, G. H., and Low, F. J. 1975, *Ap. J.*, **197**, 17.
Scoville, N. Z., Becklin, E. E., Young, J. S., and Capps, R. W. 1983, preprint.
Scoville, N. Z., Young, T. S., and Lucy, L. B. 1983, *Ap. J.*, **270**, 443.
Stein, W. A., Gillett, F. C., and Merrill, K. M. 1974, *Ap. J.*, **187**, 213.
Telesco, C. M., Becklin, E. E., and Harper, D. A. 1980, *Ap. J.* (*Letters*), **241**, L69.
Telesco, C. M., Becklin, E. E., Wynn-Williams, C. G., and Harper, D. A. 1983, preprint.
Telesco, C. M., and Gatley, I. Y. 1981, *Ap. J. Lett.*, **247**, L11.
Telesco, C. M., and Harper, D. A. 1980, *Ap. J.*, **235**, 392.
Turnrose, B. E. 1976, *Ap. J.*, **210**, 33.
Wynn-Williams, C. G., and Becklin, E. E. 1974, *Pub. A.S.P.*, **86**, 5.

S. C. BECK: Department of Astronomy, Cornell University, Ithaca, NY, 14853

S. BECKWITH: Department of Astronomy, Cornell University, Ithaca, NY, 14853

IAN GATLEY: UK Infrared Telescope Unit, 900 Leilani Street, Hilo, HI, 96720