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Balmer Line Photometry of the 30 Doradus Nebula

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Summary. The 30 Doradus nebula was scanned at 29 strips of constant declination with a square diaphragm of 30″ × 30″ using Hα and Hβ interference filters. The absolute flux calibration was obtained from observations of six planetary nebulae. Maps, integrated fluxes, and peak brightness values are given. The ratio between the Hα and Hβ intensities is compared with the theoretical value obtained from recombination theory, to calculate the amount of interstellar reddening. The visual absorption fluctuates rapidly from point to point, but there is a systematic increase from about $0^m.7$ to more than 2^m in the NW to SE direction. Comparing optical with radio data, the mean visual absorption is $1^m.2$.

Key words: Photoelectric photometry — 30 Dor nebula — Balmer lines — interstellar absorption

I. Introduction

The 30 Doradus nebula in the Large Magellanic Cloud (LMC) is a giant H II region with a complex filamentary structure and strong internal motions, apparently excited by a cluster that includes at least nine Wolf-Rayet stars (Feast, 1961). Schmidt-Kaler and Feitzinger (1976) consider it to be the nucleus of the LMC. The region has been the object of several studies, including those by Doherty et al. (1956), Faulkner (1967), Davies et al. (1976), Elliot et al. (1977) using photographic photometry; photoelectric spectrophotometry by Faulkner and Aller (1965), Mathis (1965), Aller et al. (1974); Fabry-Perot interferograms by Smith and Weedman (1972). Being a strong radio source, 30 Doradus appears in several radio surveys, e.g. McGee et al. (1972) in the 6 cm continuum; McGee and Milton (1966) in the 21 cm line; McGee et al. (1974) in radio recombination lines. In the present paper we report photoelectric observations made by scanning the nebula at the Hα and Hβ emission lines using interference filters. The results are used to estimate the amount of interstellar reddening in the area.

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II. Observations and Data Reduction

The observations were made on the 50 cm aperture Cassegrain telescope of the Observatory of the Universidade Federal do Rio Grande do Sul, using an EMI 9658 AR photomultiplier cooled with dry ice, and two interference filters centered at the Hα and Hβ lines. Their peak transmission $T_{\rm filter}$ and half-intensity widths $\Delta\lambda$ as well as the quantum efficiency Q of the detector are given in Table 1. The photon counting equipment and the data acquisition system were described by Rochol and Strauss (1975).

The 30 Doradus nebula was scanned in Right Ascension from West to East through a square focal plane aperture of 30″ × 30″ at intervals of 30″ in declination; the beginning and separation of the scans were determined by off-setting from a field star. Each data point is the result of a 2 s photon counting interval with no time lost between samples, corresponding to a motion of 10″.78 of the sky. This causes an overlap of ~2/3 of a beam between successive samples in a scan; we used a digital low-pass filter with weights (−1/16, 1/4, 5/8, 1/4, −1/16) which reduced the noise with essentially no loss in resolution (Strauss, 1977). A linear base line, adjusted to the end portions of each scan, was subtracted from the data. Two or more scans were made through each filter at each declination, and averaged.

The absolute flux scale was calibrated by observing through a 2′ diameter circular aperture the planetary nebulae NGC 1535, 2022, 2440 and 3242 and IC 418 and 2165, whose fluxes are known (Higgs, 1971). Small systematic differences between the nebulae (which are not standard sources) were allowed for by normalizing to the flux of NGC 2440.

The number N of photons counted per second in the Hα or

Table 1. Efficiency factors: full width at half intensity points $\Delta\lambda$ and peak transmission $T_{\rm filter}$ of the interference filters; quantum efficiency Q of the photomultiplier; overall telescope transmission $T_{\rm optics}$; and mean atmospheric extinction coefficient k (in magnitudes per unit air mass)

Line	$\Delta\lambda$	$T_{\rm filter}$	Q	$T_{\rm optics}$	k
Hα	37 Å	0.84	0.08	0.24	0.1
Hβ	30 Å	0.62	0.19	0.24	0.2

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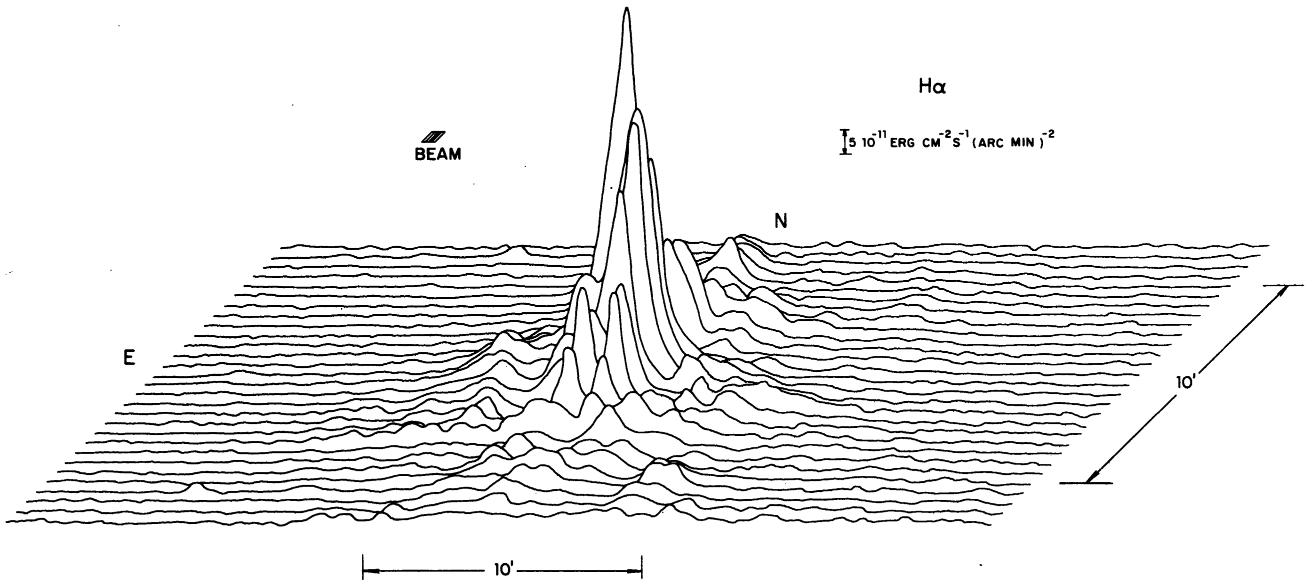

Fig. 1. Scans at constant declination of the 30 Doradus nebula. The Hα photon count measured through a 30″ × 30″ square aperture has been converted to surface brightness units

Hβ lines due to an energy flux F produced by a planetary nebula is given by

$$N = \eta AF/(h\nu), \quad (1)$$

where A is the collecting area of the telescope, $h\nu$ is the energy of a photon, and η is the efficiency of photon detection,

$$\eta = QT_{\rm filter}T_{\rm optics}10^{-0.4(\delta+kX)}, \quad (2)$$

which includes the losses in the atmosphere (k is the monochromatic extinction coefficient, X is the air mass), losses in the telescope ($T_{\rm optics}$) and in the filter ($T_{\rm filter}$), and the quantum efficiency of the detector (Q); a night correction (δ) includes small changes in the instrumental factors, and is defined such that its average over all nights is zero.

The extinction coefficient k (Table 1) was determined nightly from observations of the stars HD 38617 and HD 39014 and the night correction δ was obtained from observations of the star ε Orionis. The factor $T_{\rm optics}$ obtained by applying Eqs. (1) and (2) to the observations of planetary nebulae is given in Table 1, and is consistent with the expected losses in the two mirrors, the Fabry lens, and the double entrance window of the cold box.

In the case of Hα, there is some contamination by the [N II] lines due to the non-zero transmission of the filter at their wavelengths, which will be discussed later. The nebular continuum emission is negligible within our narrow passbands, and stellar continuum is important only near the central star (Faulkner, 1967).

III. Results and Discussion

a) Hα *and* Hβ *Fluxes*

For an extended object like the 30 Doradus nebula, the brightness at any position averaged over the solid angle Ω of our beam is

$$B = F/\Omega, \quad (3)$$

where F is obtained from Eqs. (1) and (2) using the measured counting rate N.

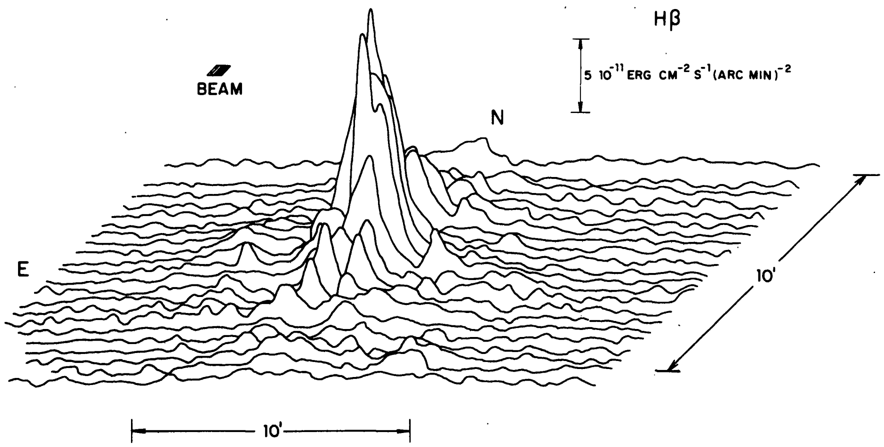

Fig. 2. Same as Fig. 1, for Hβ

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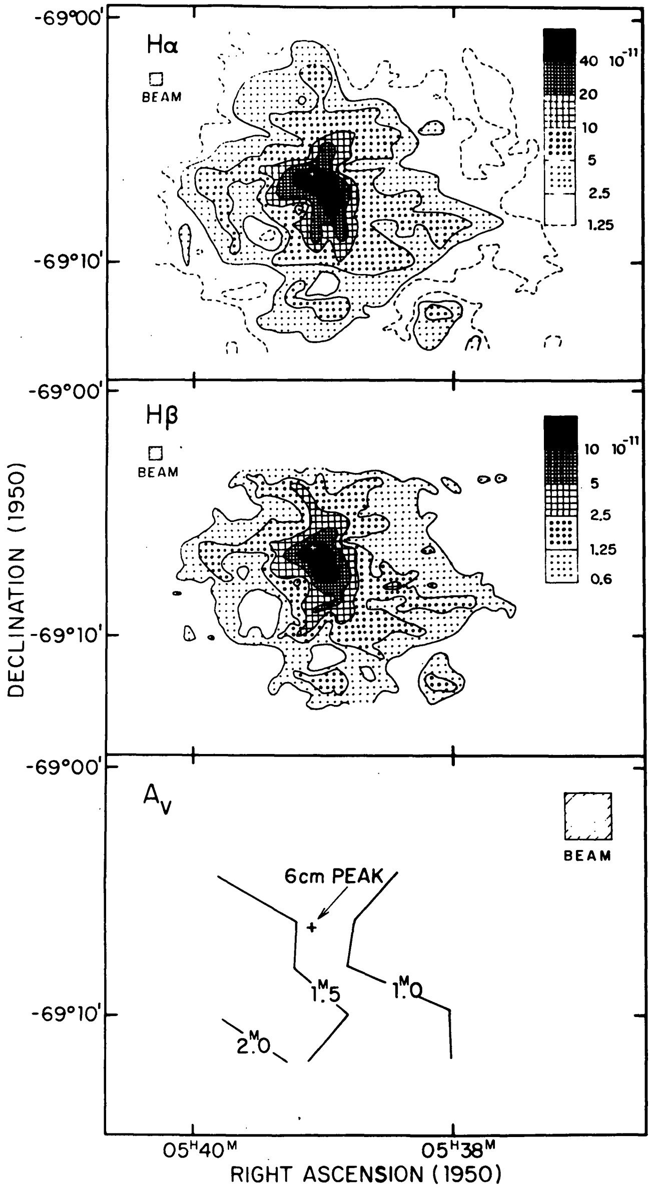

Fig. 3. The upper and middle sections are isophote maps in Hα and Hβ, respectively. The shading indicates levels of surface brightness given in units of erg cm^{-2} s^{-1} (arc $min)^{-2}$. Lower section: lines of equal visual absorption derived from the Hα/Hβ ratio after smoothing down to an equivalent 2′ × 2′ beam. Crosses indicate the peak of radio emission

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Figures 1 and 2 show the central portions of the Hα and Hβ scans, respectively. The results are also presented as isophote maps in Fig. 3, where the 1950 coordinates were obtained by reference to the positions of several field stars of the catalogue of Fehrenbach et al. (1970). The peak brightness values are

$B(\mathrm{H}\alpha) = 75\;10^{-11}\;\mathrm{erg\,cm^{-2}\,s^{-1}(arc\,min)^{-2}}$,
$B(\mathrm{H}\beta) = 17\;10^{-11}\;\mathrm{erg\,cm^{-2}\,s^{-1}(arc\,min)^{-2}}$.

The corresponding values that we derive from Fig. 3 of Mathis (1965) are about 30% lower, as expected from the lower resolution of his scans (26″ × 103″); Doherty et al. (1956), using higher resolution (8″ × 13″), obtained an Hα peak brightness that is about 50% higher than ours.

The integrated fluxes, after correction for beam overlap, are

$F(\mathrm{H}\alpha) = 10.9\;10^{-9}\;\mathrm{erg\,cm^{-2}\,s^{-1}}$,
$F(\mathrm{H}\beta) = 2.5\;10^{-9}\;\mathrm{erg\,cm^{-2}\,s^{-1}}$.

For comparison, Mathis (1965), who measured only the inner 5′ × 5′ area, obtained an integrated Hβ flux of 1.6 10^{-9} erg cm^{-2} s^{-1}.

As mentioned above, our Hα intensities suffer from contamination by the [N II] lines at 6548 and 6584 A, where the filter transmission is about 50% of the transmission at Hα. In 30 Dor, Aller et al. (1974) and Peimbert and Torres-Peimbert (1974) find values of [N II]/Hα varying between 0.04 and 0.13, which corresponds to a ratio Hα/(Hα + [N II]) of 0.93 to 0.98, corrected for filter transmission. The corresponding ratio for the six planetary nebulae we used for calibration is more uncertain. Following Higgs (1971), from where we obtained the planetary nebula fluxes, we may assume the mean ratio to be 0.75, i.e. ~0.83 with our filter. No correction would be necessary if the ratios were the same (Faulkner, 1967). Since this is not the case, we have to increase the observed values of B(Hα) by 0.93/0.83 to 0.98/0.83, i.e. by an average of 10% with a variation of ±3% at different positions. This will not affect the appearance of the Hα contour map of Fig. 3, and is within the accuracy (10–25%) of the planetary nebula fluxes (Higgs, 1971).

b) *Interstellar Absorption*

From the intensity ratio of forbidden lines in 30 Doradus, Feast (1961) and Faulkner and Aller (1965) derived an electron temperature $T_e \sim 10^4$ K and density $N_e \sim 10^2$ to $10^3\;\mathrm{cm^{-3}}$. For these values, the hydrogen recombination theory (Brocklehurst, 1971) predicts a line ratio Hα/Hβ ≅ 2.9. Thus, from the measured line ratio at each point we may obtain a color excess

$$E_{\beta-\alpha} = 2.5 \log\{[B(\mathrm{H}\alpha)/B(\mathrm{H}\beta)]/2.9\}\,. \quad (4)$$

The reddening law in the region seems to be normal, with a total to selective extinction ratio $R = 3$ (Walker and Morris, 1968). Hence, the visual absorption is (Miller and Mathews, 1972)

$$A_v = 2.59\,E_{\beta-\alpha}\,. \quad (5)$$

We applied Eqs. (4) and (5) to our data and found that the absorption fluctuates rapidly from point to point, as reported by Mathis (1965). To investigate the existence of systematic trends, we averaged the data to a resolution of 2′ × 2′. The resulting map (Fig. 3) shows the existence of an absorption gradient, with visual absorption increasing from $0^m\!.7$ to more than 2^m in the NW to SE direction. Such an effect can also be inferred from the photograph of the region published by Johnson (1968, Plate 8) where the star count is larger on the upper right than on the lower left.

The mean absorption, obtained from the ratio of the total fluxes, is $A_v = 1^m\!.1$. For comparison, Mathis (1965) reports a mean absorption at Hβ of $A_\beta \cong 0^m\!.5$ (corresponding to $A_v \cong 0^m\!.4$); Aller et al. (1974) give $A_\beta \cong 1^m (A_v \cong 0^m\!.9)$; Faulkner and Aller (1965) find A_v values between $0^m\!.2$ and $1^m\!.1$ at eight bright points of the nebula; Borgman and Danks (1977) from *uvbyR* surface photometry, find $0^m\!.2 < E_{B-V} < 0^m\!.5$ ($0^m\!.6 < A_v < 1^m\!.5$). No systematic trends were reported. The lower values of A_v are not surprising since obscuration in this, as in

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other H II regions, is very patchy, and most observations are made in the brightest (and generally less obscured) regions.

c) Comparison with Radio Observations

Several radio maps of the 30 Doradus region are available. The integrated fluxes at 6, 11, 21 and 73 cm wavelengths have been summarized by McGee and Newton (1972). The 6 cm peak (McGee et al., 1972) indicated in Fig. 3, coincides with the maximum of optical emission within the accuracy of the respective observations.

Assuming that the nebula is optically thin both at the Balmer lines and at radio wavelengths, the total radio flux can be used to predict the integrated optical emission. Combining the free-free emission coefficient of Oster (1961) with the Balmer line emissivity of Brocklehurst (1971) we obtain the expected optical flux. We used $T_e = 10^4$ K and a ratio of He to H of 0.08 (Peimbert and Torres-Peimbert, 1974; McGee et al., 1974). Comparing the Hβ fluxes predicted by the radio data at the above four wavelengths with the observed Hβ flux, and assuming the standard reddening law with $R = 3$, we obtain the mean absorption $A_v = 1^m.2$ which is very similar to the mean value obtained independently above ($A_v = 1^m.1$) using only optical data. Actually, the latter has to be somewhat increased to correct for the contamination of Hα by [N II]. We point out that the uncertainty in the theoretical Hα/Hβ ratio used in Eq. (4) and in the reddening law causes an uncertainty of at least 0.2 mag in the A_v values which therefore have to be treated with caution. This will not affect our conclusion that an absorption gradient of about one magnitude exists over the 30 Dor region.

Le Marne (1968) compared a radio map at 408 MHz (with resolution $\sim 3'$) with Faulkner's (1967) photographic isophotometry of the nebula and obtained a good fit with a model with $R = 7$ in which A_v decreases from 2^m at the center to $0^m.8$ at the outskirts, but because of insufficient resolution this model is not unique. In view of this problem, we have not attempted a similar detailed comparison.

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