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STUDY OF THE NUCLEI OF NGC 3732 AND IC 4662

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ABSTRACT

The nuclei of two galaxies which show intense [O III] emission lines, NGC 3732, an Sa, and IC 4662, an irregular with a very bright nucleus, are analyzed spectroscopically. The physical condition of the emitting gas and the characteristics and relative degree of evolution of the ionizing sources are discussed.

It was found that the principal differences between the line spectra of both objects are due to abundance effects, although there is some evidence suggesting a different degree of evolution of the ionizing stars.

Subject headings: galaxies: individual — galaxies: nuclei

I. INTRODUCTION

Many authors have investigated the origin of the emission-line intensity ratios observed in H II regions, as well as in nuclei of galaxies, principally for the [N II]/Hα, [O II]/Hβ, [O III]/Hβ, and [N II]/[O II]. Although it is generally accepted that the physical conditions of the gas are responsible for the variety of relative intensities actually observed in different objects, Peimbert (1968) has shown that for the nuclei of M51 and M81 the observed characteristics of the emission-line spectra, are principally due to a different chemical composition than that observed in the solar neighborhood. Gradients of chemical composition in the H II region across the disks of spiral galaxies were also found to be the best explanation for the observed line-intensity ratios in many regions of M33 and M101 (Searle 1971).

In this paper two objects of different morphological type, IC 4662, an irregular with a very bright condensation, and NGC 3732, a spiral of type SA with a very small, extremely bright nucleus (de Vaucouleurs 1964), were selected from a group of galaxies showing strong [O III] lines, in order to make a comparative study. Arguments are given showing that although differences in chemical composition should be found between both objects, there should also exist a different degree of evolution of the ionizing source.

II. OBSERVATIONS

The Westinghouse fiber-optics image tube with the Cassegrain spectrograph of the 60 inch (1.52 m) telescope of Cerro Tololo Inter-American Observatory was used to obtain several spectra at a dispersion of 114 Å mm^{-1}, covering the range $\lambda\lambda$4000–7500. The observed emission lines and their intensities relative to Hβ are listed in Table 1. The stronger emission lines, Hα, Hβ, [O III] λ4959 and λ5007, and [O II] λ3727 were also observed with the dual-channel computer-controlled scanner attached to both the 60 (1.52 m) and 36 inch (0.91 m) telescopes, during 1973 April and May. The measured intensities were reduced to ergs cm^{-2} s^{-1} outside the Earth's atmosphere by standard techniques, based on a mean of the Hayes (1970) and Oke and Schild (1970) calibrations. The observed intensities in the emission lines are listed in Table 2. Scans of the continuum, covering discrete points in the wavelength range between λ3500 and λ7200, were obtained for IC 4662 (Table 3). Since we have not measured the continuum for NGC 3732, only approximate values from the neighborhood of the emission lines between λ3700 and λ6500 were derived.

The observed fluxes were corrected for reddening by comparing the observed Hα/Hβ ratio with the expected intrinsic one. Under the case B condition of Baker and Menzel (1938), radiative recombination should produce an Hα/Hβ ratio of about 2.8 (Pengelly 1964). By assuming linear dependence of the absorption on $1/\lambda$ and $A_v = 3E(B-V)$, A_λ can be calculated as a function of the observed Hα/Hβ ratio:

$$A_\lambda = \left(\frac{4.69}{\lambda} - 1.45\right)\log\frac{\mathrm{H}\alpha}{2.8\mathrm{H}\beta} \qquad \text{(Mathis 1970)},$$

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TABLE 1

Observed Line Intensities Relative to Hβ

Ion	Line	IC 4662 $I/I_{H\beta}$	NGC 3732 $I/I_{H\beta}$
[S II].....	6730	0.3	0.7
[S II].....	6717	0.2	0.7
[N II].....	6583	0.1	1.7
H I	6562 }	3.2	2.9
[N II].....	6548 }		1.4
[O III]....	5007	4.7	0.8
[O III]....	4959	3.1	0.4
H I	4861	1.0	1.0
H I	4340	0.7	0.4
H I	4101	0.1	...
[Ne III]...	3868	0.6	...
[O II].....	3727	2.0	...

TABLE 2

Absolute Intensities of the Strongest Emission Lines

Ion	Line	IC 4662 $F_\nu \times E(12)$ (ergs s^{-1} cm^{-2})	IC 4662 W (Å)	NGC 3732 $F_\nu \times E(13)$ (ergs s^{-1} cm^{-2})	NGC 3732 W (Å)
[S II]....	6730 }	0.39	...	...	...
[S II]....	6717 }				
[N II] ...	6583 }				
H I.....	6562 }	4.7	419	13.0	80
[N II] ...	6584 }				
[O III]...	5007	7.8	244	...	...
[O III]...	4959	2.2	126	...	...
H I.....	4861	1.23	79	2.5	11
[O II]....	3727	2.65	109	3.6	20

TABLE 3

Observed Flux and Absorption in the Continuum of IC 4662

λ (Å)	$F_\nu \times E(24)$ (ergs s^{-1} cm^{-2} Hz^{-1})	A_λ (mg)
7100...	0.184	0.59
6050...	1.138	0.73
5270...	0.130	0.86
4050...	0.122	1.17
3700...	0.108	1.29
3570...	0.110	1.35

TABLE 4

Line Intensity Ratios Corrected for Absorption

Galaxy	log [O III]/Hβ	log [O II]/Hβ	log Hα/[N II]	log [O II]/[N II]	$E(-39)\mathcal{L}_{H\beta}$ (ergs s^{-1})
IC 4662......	0.90	0.46	+1.36	+1.37	5.3
NGC 3732...	0.06	0.20	−0.03	−0.20	8.8

where λ is in microns. The absorption in Hα was estimated to be 1.44 mag for NGC 3732 and 0.94 mag for IC 4662. Table 4 gives in succession the corrected line-intensity ratios, log [O II]/[N II], log Hα/[N II], and log [O III]/Hβ, as well as the luminosity in Hβ of both galaxies.

The distance of NGC 3732 was derived from the corrected mean radial velocity $V_r = 1539$ km s^{-1}, by adopting a Hubble constant $H = 100$ km s^{-1} Mpc^{-1}. For IC 4662, a true distance modulus of $m - M = 28$ was adopted (Pastoriza 1970).

III. THE CHEMICAL ABUNDANCE, TEMPERATURE, AND ELECTRON DENSITY

From the equations and assumptions given by Peimbert and Costero (1969), it is possible to obtain the abundances of the different ions relative to H II as a function of the electronic temperature, T_e. The necessary relations are:

$$\frac{N(\mathrm{O\,II})}{N(\mathrm{H\,II})} = (7.2\times10^{-5})\frac{1+7.6x+6.8x^2}{1+5.6x}T_e^{\,-0.375}\times\frac{I(3727)}{I(\mathrm{H}\alpha)}\exp\left(\frac{3.86\times10^4}{T_e}\right),$$

$$\frac{N(\mathrm{O\,III})}{N(\mathrm{H\,II})} = 1.65\times10^{-4}(1+0.01x)T_e^{\,-0.375}\times\frac{I(5007)}{I(\mathrm{H}\alpha)}\exp\left(\frac{2.89\times10^4}{T_e}\right),$$

$$\frac{N(\mathrm{N\,II})}{N(\mathrm{H\,II})} = 1.65\times10^{-4}(1+0.14x)T_e^{\,-0.375}\times\frac{I(6584)}{I(\mathrm{H}\alpha)}\exp\left(\frac{2.20\times10^4}{T_e}\right),$$

where $x = 10^{-2}N_eT_e^{\,-1/2}$. The total oxygen-to-hydrogen abundance is derived assuming that each oxygen atom is either singly or doubly ionized; therefore,

$$\frac{N(\mathrm{O})}{N(\mathrm{H})} = \frac{N(\mathrm{O\,II})+N(\mathrm{O\,III})}{N(\mathrm{H\,II})}.$$

Because the ionization potential of N II and O II are similar, it is assumed that

$$\frac{N(\mathrm{N})}{N(\mathrm{H})} = \frac{N(\mathrm{O\,II})+N(\mathrm{O\,III})}{N(\mathrm{O\,II})}\times\frac{N(\mathrm{N\,II})}{N(\mathrm{H\,II})}.$$

The quantity $x = 10^{-2}N_eT_e^{\,-1/2}$ necessary to carry out the computations was obtained from the intensity ratio of the [S II] doublet λ6717/λ6730 (Osterbrock 1974).

The abundances are derived from the line-intensity ratios corrected for reddening (Table 4) for a range of temperatures from 5000 K to 13,000 K, for both galaxies. For NGC 3732, a normal abundance of oxygen $N(\mathrm{O})/N(\mathrm{H}) \approx 6\times10^{-4}$, like that deduced by Peimbert and Costero (1969) for the Orion Nebula I, II, and III, requires a temperature $T_e = 6900$ K, which in turn leads to an overabundance of nitrogen by a factor of 2.5. For IC 4662 a normal oxygen abundance demands a temperature $T_e = 8500$ K and leads to a remarkably low nitrogen abundance $N(\mathrm{N})/N(\mathrm{H}) \approx 6\times10^{-6}$. On the other hand, a normal nitrogen abundance would lead to the following situation: In NGC 3732, $T_e \approx 5600$ K, and $N(\mathrm{O})/N(\mathrm{H}) \approx 4\times10^{-3}$. In IC 4662 $T_e < 5000$ K and $N(\mathrm{O})/N(\mathrm{H})$ a hundred times greater than normal.

The excess of N in NGC 3732 would be in agreement with previous results obtained by Peimbert (1968) and Searle (1971) for the central regions of other spiral galaxies. For IC 4662 we would adopt the picture of underabundance of nitrogen, suggesting that this is a metal-poor system like the LMC (Dufour 1973).

The electron density was computed, under the assumed electronic temperature ($T_e = 6900$ K for NGC 3732 and $T_e = 8500$ K for IC 4662), from the line intensity ratio of the [S II] doublet at λλ6717 and 6730. The values obtained were $N_e = 600$ cm^{-3} and 1500 cm^{-3}, respectively.

IV. IONIZING SOURCE

The close similarity of the emission-line spectra of both galaxies to those of the H II region observed by Searle (1971) is strong evidence that hot stars are responsible for the ionization. The number and spectral-type distribution of the hot stars necessary as an ionizing source in the nuclear region of both galaxies can be derived following the procedure used by Osmer, Smith, and Weedman (1974), from the observed luminosity of Hβ, assuming a given birth-rate function. The necessary relations are:

i) The total number of Lyman photons per second for the galaxy $N_t = 2.0\times10^{12}L_{\mathrm{H}\beta}$

ii) The total number of Lyman continuum photons per star, for the spectral types listed by Morton (1969), $4\pi R^2 N_{\mathrm{Ly}} = 1.34\times10^{35}(N_{\mathrm{Ly}}/\pi F_v)\mathrm{dex}(-0{,}4\ M_v)$ photons s^{-1}, where M_v is the absolute visual magnitude

iii) The Salpeter initial luminosity function of the form $\phi(m)=\alpha m^{-2.45}$, where m is the stellar mass and ϕ is the number of stars formed of mass m

Under these conditions the total number of Lyman photons for each galaxy (N_t) is

$$N_t = \phi_{\mathrm{O5}} \sum_i \left(\frac{m_i}{m_{\mathrm{O5}}}\right)^{2.45} N_{\mathrm{Ly}_i},$$

where i runs over the spectral types from O5 to B5, and N_{Ly_i} is the total number of Lyman photons emitted by a star of spectral type i. The total number of ionizing stars is derived from the number of O5 stars and the equation from (iii) above. The total mass of young stars generated together with the ionizing stars was computed adopting 0.75 and 0.00 $M_{\odot}$ as lower limits for the integral of $\phi(m)$. The number of O5 stars (ϕ_{O5}), the total number of ionizing stars ($\phi_{\star}$), the total mass of ionizing stars (MIS), and the total mass of young stars (MYS), are listed in Table 5. The de-reddened Lyman Hβ allows us to compute the mass ($M_{\mathrm{H\,II}}$) and the volume ($V_{\mathrm{H\,II}}$) occupied by the ionized gas. These results are listed in Table 5.

V. COMPARISON OF THE EMITTING REGIONS

The equivalent width of the Hβ line ($W_{\mathrm{H}\beta}$) and the parameter of excitation [O III]/Hβ indicate some actual differences between the emitting region of both galaxies. In fact the $W_{\mathrm{H}\beta}$ for NGC 3732 is one-tenth that of IC 4662, indicating, under the assumption of the same birth-rate function, that (1) the regions are in the mean older in NGC 3732, (2) the contribution from cold stars of the surrounding medium is higher in NGC 3732, or (3) both reasons simultaneously.

From the [O III]/Hβ ratio and the electronic temperature, it is possible to deduce the value of the "ionizing factor" ε, using Searle's (1971) diagram 6. The deduced values are $\varepsilon=15/16$ for NGC 3732 and $\varepsilon=3/4$ for IC 4662. According to Searle (1971), the closer ε is to 1, the cooler is the ionizing source. Therefore, under the assumed hypothesis, the ionizing stars operating in NGC 3732 should be in the mean older than those in IC 4662. Nevertheless, it is not possible to discard a higher contribution from the surrounding medium to the continuum at Hβ for the spiral galaxy.

VI. THE CONTINUUM

The observed energy distribution of IC 4662, corrected for reddening by means of the relationship given above, was compared with that of M51 (Fig. 1). The continuum of IC 4662 is flatter, indicating a higher relative flux on the UV side of the spectrum.

With the data available from the emission spectra, it is possible to estimate the contribution of the emitting gas to the continuum at a given wavelength (Andrillat, Souffrin, and Alloin 1972), by applying the following relation:

$$\left[\frac{I_{\mathrm{therm}}}{I_{\mathrm{cont}}}\right]_{\nu} = \frac{hW_l}{F_l(N_e,T_e)}\,\frac{I_{c_l}}{I_{c_\nu}}\,\gamma_\nu(N_e,T_e).$$

The terms on the right-hand side of the equation are, respectively,

h = the Planck constant

W_l = the equivalent width in Hz of the emission line selected to compute the contribution

TABLE 5

PHYSICAL PROPERTIES OF THE EMITTING REGIONS

Region	ϕ_{O5}	$\phi_{\star}$	MIS [$E(4)M_{\odot}$]	MYS [$E(6)M_{\odot}$]	$M_{\mathrm{H\,II}}$ [$E(4)M_{\odot}$]	$E(-50)\ V_{\mathrm{H\,II}}$ (cm^3)
NGC 3732...	246	4080	36.4	1.9[a] 2.3[b]	11.6	2.43
IC 4662......	148	2460	7.4	1.1[a] 1.4[b]	2.4	0.16

[a] Integration lower limit 0.73 $M_{\odot}$.
[b] Integration lower limit 0.00 $M_{\odot}$.

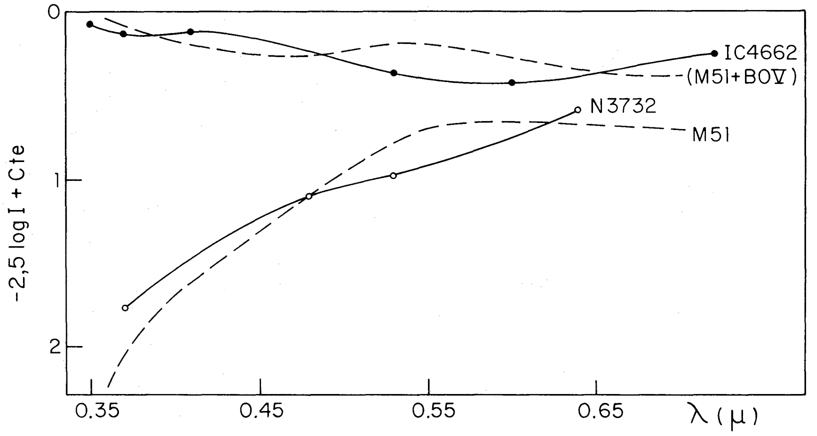

FIG. 1.—Fit of the continuum of both galaxies with that of M51. See text.

f_l = the coefficient of emissivity related to the intensity of the line by $I_{\rm line} = VN_e{}^2F(N_e, T_e)$ ergs $\rm s^{-1}$

I_{c_l} = the intensity of the continuum at the frequency of the selected line

I_{c_ν} = the intensity of the continuum at the frequency where the contribution from the hot gas will be evaluated

$\gamma(N_e, T_e)$ = the emissivity of the hot gas calculated for $f-f$, $f-b$, and two-photon processes (Seaton 1960). It is related to the thermal flux of the hot gas by $I_{\nu_{\rm therm}} = hVN_e{}^2\gamma(N_e, T_e)$.

We have adopted the doublet λλ(4959–5007) of the [O III] as reference line. The contribution of the gas was evaluated on the UV side of the Balmer jump (B^-), and the values used to carry out the computation were:

$$W_{(4959+5007)} = 8.3\times10^{13}\ \rm Hz;$$

$$f_{(4959+5007)} = 9.7\times10^{-25}\ \rm ergs\ cm^{-2};$$

$$I_c(5007)/I_{B^-} = 0.76;$$

$$\gamma_{B^-} = 4.2\times10^{-3}\ \text{for } T_e = 8500\ \rm K,\ \text{and } N_e = 1.5\times10^3\ cm^{-3}.$$

The proportion obtained was $[I_{\rm ther}/I_{\rm cont}]_{B^-} = 0.18$.

The deduced gas contribution to the continuum, although large for the shorter-wavelength side of the Balmer jump, is not enough to explain the flatness of the optical continuum of IC 4662.

The high value of the equivalent width of Hβ in IC 4662 (W=79 Å) compared with that of M51 (W=2 Å computed from data of Peimbert) suggests that a normal way to explain the flatness of the continuum of IC 4662 would be through early-type stars. We have carried out a series of fittings, adding to the continuum of M51 different proportions of B0 V stars. The best agreement was reached with early-type stars contributing 75% to the total continuum at λ5360, as shown in Figure 1. The corrected energy distribution of NGC 3732, fits well with that of M51 (also Fig. 1).

VII. CONCLUSION

The previous analysis seems to point out that the principal differences between the line spectra of both objects are due to abundance effects, although there is some evidence suggesting a different degree of evolution of the ionizing stars. The steepness of the continuum of IC 4662, which would be explained simply by adding a high proportion of early-type stars, to one similar to that of NGC 3732, would reinforce the suggestion that the ionizing source is younger in the former case.

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