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ON THE [S II] AND [O I] LINE INTENSITIES IN GASEOUS NEBULAE AND NUCLEI OF GALAXIES

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SUMARIO

Se presentan nuevas observaciones fotoeléctricas de las intensidades de las líneas prohibidas de azufre una vez ionizado correspondientes a los núcleos de las galaxias M51 y M81. Se encuentra que en regiones H II normales, núcleos de galaxias y un remanente de supernova los cocientes *I*[S II]/*I*[O I] son muy semejantes aún cuando los cocientes *I*[O I]/*I*[O III] difieren hasta por un factor de mil. Este resultado implica que las líneas prohibidas de oxígeno neutro y azufre una vez ionizado se originan en las mismas regiones. Se demuestra que en estas regiones una fracción considerable de los átomos de oxígeno se encuentra ionizada.

ABSTRACT

We present new photoelectric observations of the [S II] line intensities in the nuclei of M51 and M81. It is shown that the [S II]/[O I] line intensity ratios are very similar in objects where the [O I]/[O III] line intensity ratios differ by as much as three orders of magnitude; these objects comprise normal H II regions, nuclei of galaxies and a supernova remnant. This result strongly suggests that the [O I] and [S II] lines originate in the same regions. It is shown that in the regions where the [O I] and [S II] lines originate a considerable fraction of the oxygen is ionized.

In Table 1 we give the [S II] line intensities of M51 and M81 relative to those of Hα, Hβ, [O III] and [O I]; the observations were obtained in 1968 with the 120-inch telescope and the photoelectric scanner designed by Wampler (1966, 1967) at Lick Observatory; the observing procedure was similar to that reported by Peimbert (1968). Included in Table 1 we also present the intensities for the Seyfert galaxy NGC 4151 (Oke and Sargent 1968) as well as the unreddened line intensities assuming a logarithmic reddening correction $C(\mathrm{H}\beta) = 0.43$ (Osterbrock 1971) and the normal reddening law.

TABLE 1

Line Intensities

		M51*	M81*	NGC 4151	
Wavelength	*Identification*	log $B^{\dagger}I(\lambda)/I(\mathrm{H}\alpha)^{\ddagger}$	log $BI(\lambda)/I(\mathrm{H}\alpha)$	log $BF(\lambda)/F(\mathrm{H}\alpha)^{\S}$	log $BI(\lambda)/I(\mathrm{H}\alpha)$
4861	Hβ	—	+0.04	+0.08	+0.08
5007	[O III]	+0.50	+0.13	+0.41	+0.40
6300	[OI]	−0.31	−0.17	−0.66	−0.79
6563	Hα	+0.46	+0.46	+0.61	+0.46
6716 + 6731	[S II]	+0.35	+0.12	−0.20	−0.37

* Centered in the galaxy with a diaphragm 3.5″ in radius.

† log B = 0.46.

‡ *I* is the intrinsic flux after correcting for reddening in ergs $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$.

§ *F* is the observed flux in ergs $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$.

The ionization potential of neutral oxygen is almost the same as that of hydrogen and consequently the [O I] lines should originate either in H I regions or in partially ionized regions (namely, boundaries between H II and H I regions, volumes partially ionized by X-rays or cosmic rays, and recombination regions where the ionizing source no longer plays a role). Alternatively the [S II] lines are expected to originate either in the spots of lowest degree of ionization of H II regions, in partially ionized regions, or in the H I regions themselves since the S° ionization potential is only 10.36 eV. Under the assumption that the excitation of the [O I] and [S II] lines is collisional and that they originate in the same region, their intensity ratio can be expressed as

$$\frac{I\,(6300)}{I\,(6716+6731)} = \frac{N(\mathrm{O}^{\circ})}{N(\mathrm{S}^{+})}\;\frac{1.9\times10^{-5}}{f\,(x,T_e)}\;T_e^{0.82}\exp\left(-1.40\times10^{3}/T_e\right), \qquad (1)$$

where $x = 10^{-2} N_e T_e^{-1/2}$ and $f(x, T_e)$ takes into account the collisional de-excitation of the D levels of the S^+ atom and is smaller than unity (Henry and Williams 1968; Wiese, Smith and Glennon 1966; Saraph and Seaton 1970; Krueger, Aller and Czyzak 1970; Czyzak and Krueger 1963, 1965). The temperature dependence of equation (1) is relatively small.

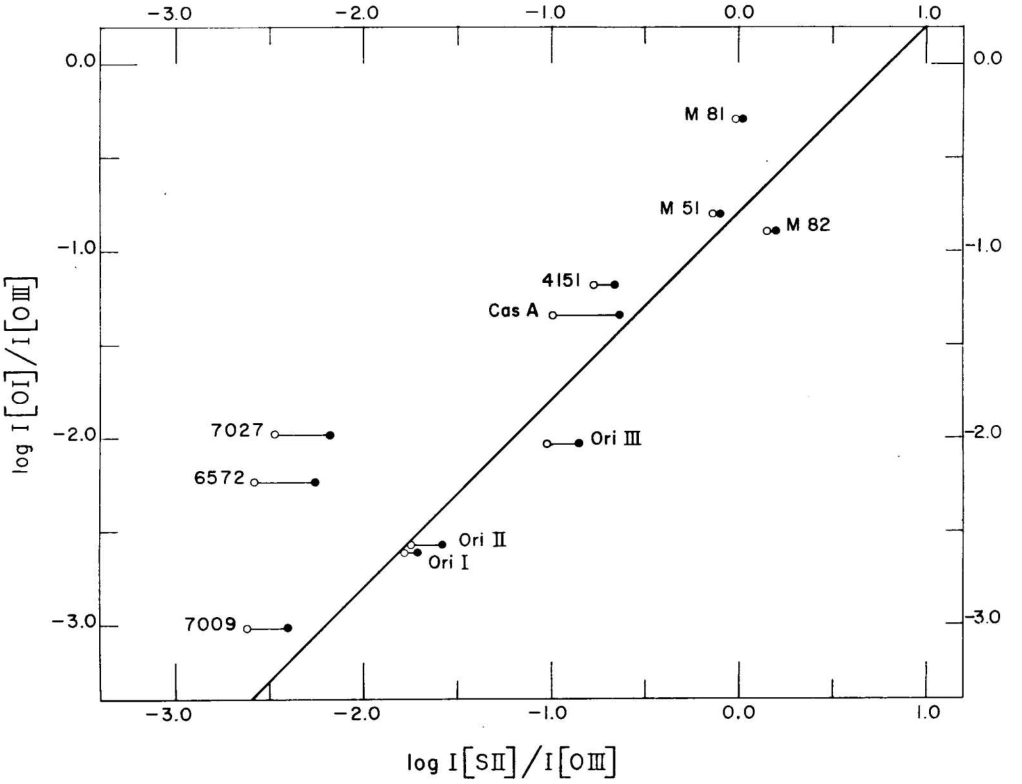

Fig. 1.—*Open circles represent the intrinsic intensities. Filled circles* I[*O I*]/I[*O III*] vs. *I* [*S II*]/I[*O III*] f (x, T_e).

In Figure 1 the $I(6300)/I(5007)$ *vs.* $I(6716 + 6731)/I(5007)$ ratios are represented for eleven different objects from observations by Peimbert and Costero (1969), Peimbert and Torres-Peimbert (1971), Peimbert (1968), Peimbert and Spinrad (1970), Searle (1971) and the data presented in Table 1. The open circles represent the observed intensity ratios. The [O I] and [O III] line intensities are proportional to the second power of the density for the physical conditions encountered in the objects under discussion. However, the [S II] lines behave as N^2 at low densities but at higher densities they become less density-dependent due to collisional de-excitations of the D levels. In Figure 1 the filled circles represent the I[O I]/I[O III] *vs.* I[S II]/I[O III] $f(x, T_e)$ ratios where f has been defined in equation (1). To compute f we have adopted $T_e = 10000$°K and the x values presented in Table 2. When no direct computation of x (S II) was available we used x (S II) $= 2x$ (O II) (Peimbert 1971*a*). From Figure 1 it is clear that with the exception of NGC 6572 and NGC 7027 there is a good correlation between the [O I]/[O III] and the [S II]/[O III] line intensity ratios which covers nearly three orders of magnitude. Since differences in chemical abundance ratios and electron temperatures are expected to produce negligible differences in comparison with the three orders of magnitude for which the correlation holds it follows that the [O I] and [S II] lines originate in the same regions and consequently that equation (1) is valid.

TABLE 2

Adopted Densities

Object	x (S II)	*Object*	x (S II)	*Object*	x (S II)
Ori I	0.4	NGC 6572	2.3	M82	0.0
Ori II	1.1	NGC 7027	1.9	NGC 4151	0.5
Ori III	0.8	M51	0.1	Cas A	2.8
NGC 7009	1.0	M81	0.2		

To derive the $N(O^\circ)/N(S^+)$ abundance ratio from equation (1) it is necessary to know the electron temperature. The temperature is not expected to be higher than about 12000°K because otherwise oxygen would get collisionally ionized; nor smaller than about 7000°K as evidenced by the high $I(4069 + 4076)/I(6716 + 6731)$ ratios observed in the Orion Nebula, planetary nebulae, NGC 4151 and Cas A; consequently the assumption of $T_e = 10000$°K seems to be reasonable.

With $T_e = 10000$°K, the I[O I]/I[S II] value plotted as the correlation line in Figure 1 and equation (1) we find $N(O^\circ)/N(S^+) = 5$. This abundance ratio is approximately a factor of four smaller than the $N(O)/N(S)$ abundance ratio found by Peimbert and Costero (1969) in H II regions; the result by Peimbert and Costero is mainly based on I[S III] and I[O II] lines which originate inside the H II regions. Combining both results we have $4N(O^\circ)/N(S^+) = N(O)/N(S)$; then assuming that in these regions $N(S) = N(S^+)$ it follows that $4N(O^\circ) = N(O)$, i. e., oxygen is about 25% neutral and 75% ionized. This result is reasonable because if oxygen is partially ionized presumably hydrogen is partially ionized too; and consequently the hydrogen atoms are able to provide the free electrons needed to collisionally excite the [O I] and [S II] lines.

It is clear from Figure 1, that in the Orion Nebula the partial ionization regions, where the [O I] and [S II] lines originate, are considerably more important in Ori III than in Ori I and Ori II; similarly it can be argued that the partial ionization regions are by far more important in the nuclei of galaxies than in normal H II regions of the solar neighborhood.

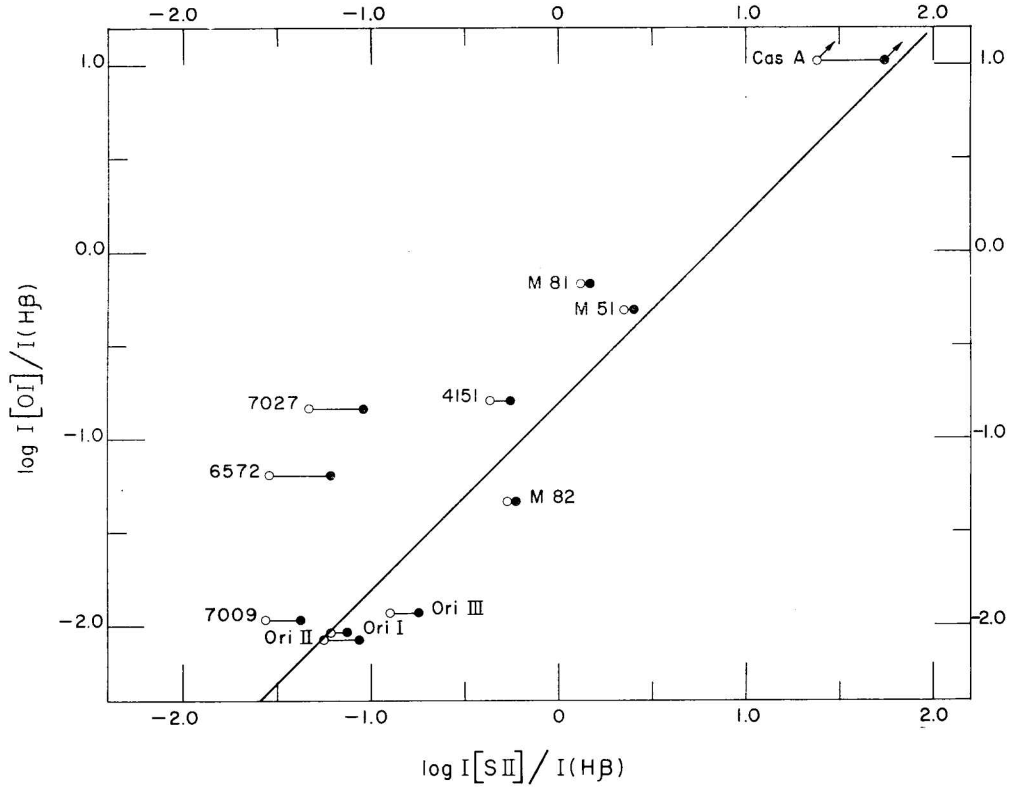

Fig. 2.—*Open circles represent the intrinsic intensities. Filled circles* I[O I]/I(Hβ) vs. I[S II]/I(Hβ) f(x, T_e). *In Cas A Hβ has not been detected.*

In Figure 2 we show the I[O I]/I(Hβ) *vs.* I[S II]/I(Hβ) ratios. An object can have higher forbidden-to-Hβ line intensity ratios than another object due to one or a combination of the following circumstances: *a)* higher oxygen to hydrogen and sulphur to hydrogen abundances; *b)* a higher proportion of regions of partial ionization; *c)* higher electron temperatures. For example it is expected that the abundances in the Orion Nebula are the same at different spots, therefore the position of Ori III relative to Ori I and Ori II in Figure 2 is partly due to the higher predominance of the partial ionization regions in Ori III; furthermore the relative position of Cas A with respect to Ori III is largely due to differences in chemical abundances (Peimbert and van den Bergh 1971; Peimbert 1971*b*). From the previous discussion it follows that from the I[S II]/I(Hα) ratios alone it is not possible to decide between possibilities *a, b* or *c.*

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