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THE EFFECT OF SHOCK WAVES ON THE SPECTRA OF H II REGIONS AND PLANETARY NEBULAE[1]

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ABSTRACT

Emission lines from H II regions and planetary nebulae are contaminated by shock waves produced by stellar winds and supernova remnants. This effect is studied and it is found that it could be responsible for: (a) the difference between the O/H abundances derived from the O nebular lines coupled with H II region models and those derived from the observed $I(4363)/I(5007)$ ratio, (b) the large t^2 values observed in the Orion nebula and M 8, (c) the difference between the stellar and the H II region O/H abundances in the solar neighborhood, (d) the large [S II]/Hα ratios observed in H II galaxies, and (e) the low O/H ratios and the N/O versus O/H anticorrelation found in Type I PN and shell nebulae around Population I stars.

Key words: H II regions–nebulae: abundances–nebulae: supernova remnants–nebulae: planetary

1. Introduction

It is generally assumed that the energy input to H II regions and planetary nebulae (PN) is due to photoionization and that shock waves do not play an important role in the emission-line spectra. In this article we will explore the effect that shock waves can have on the emitted spectra and particularly on the determined chemical abundances.

There are arguments that indicate that for most objects the shock-wave effect cannot be larger than ~ 0.4 dex in the O/H ratio. These are: (a) the presence of abundance gradients derived in the Galaxy and other galaxies from H II regions (e.g., Shaver et al. 1983; Torres-Peimbert, Peimbert & Fierro 1989) and in the Galaxy from Type II PN (Maciel 1991) and (b) from the comparison of the abundances derived from different positions in the same H II region (e.g., Peimbert & Torres-Peimbert 1977; Diaz et al. 1987).

On the other hand, there are many pieces of evidence that indicate the presence of shock waves inside H II regions and PN that could affect the O/H ratios by as much as 0.4 dex. In what follows we will discuss the evidence in favor of the presence of shock waves and some possible consequences of such presence.

2. Extragalactic H II Regions

2.1 *Observational Evidence*

Five out of eight oxygen-rich supernova remnants are found inside H II regions (van den Bergh 1988). Five out of eleven known supernovae of Type Ib exploded in H II regions (Wheeler, Harkness & Capellaro 1987).

To estimate the significance of these results we present in Table 1 the fraction of early-type stars inside H II regions in the Galaxy. The fraction of stars in H II regions was taken from Torres-Peimbert, Lazcano-Araujo & Peimbert 1974 and Cruz-Gonaźlez et al. 1974; their studies were based on the H II regions that appear in the Palomar Red Sky Survey. The limiting brightness for detection of an H II region in this survey corresponds to an emission measure in the 17 to 40 cm^{-6} pc range (Peimbert, Rayo & Torres-Peimbert 1975). Similar

TABLE 1

Fraction of Early Type Stars Inside H II Regions

Spectral Type	Mass ($M_\odot$)	Main Sequence Lifetime (10^6 y)	Fraction in H II Regions	Lifetime in H II Regions (10^6 y)
O3	80	1.4	0.69	1.17
O4	60			
O5	50	1.6		
O5.5	45	2.0		
O6	40	2.4	0.68	1.73
O6.5	37	2.7		
O7	35	3.0	0.58	1.74
O8	30	4.0	0.46	1.84
O9	27	5.0	0.52	2.6
B0	18	10	0.21	2.1
B0.5	15	15	0.16	2.4
B1	12	24	0.12	2.9
B2	10	35	0.12	< 4.2
B3	8	56	0.19	<10.6
B5	6	100	0.17	<17.0
WR	—	—	0.39	—

[1]Based on an invited lecture given at The Texas-Mexico Conference on Astrophysics, held at Rice University at Houston, Texas, 1991 February 14–15.

results from a smaller sample of O stars were obtained by van den Bergh 1988.

The masses and lifetimes on the main sequence given in Table 1 were taken from Maeder & Meynet 1987 and Allen 1973; the last column was obtained under the assumption that all objects are in the main sequence; therefore, the values in this column have to be corrected for the presence of supergiant stars. We consider that this effect is more pronounced in the B2, B3, and B5 stars due to the larger differences between the masses and absolute magnitudes of supergiant and main-sequence stars. Since inside H II regions a larger fraction of B2, B3, and B5 supergiants than main-sequence stars is expected, the values for these spectral types should be considered as upper limits.

From Table 1 the following conclusions are made: (a) H II regions dissipate in about 2×10^6 years; (b) as discussed by van den Bergh 1988, O-rich SNRs are produced by stars with an average mass of about 30 $\mathfrak{M}_\odot$; (c) it seems that Type Ib SN are produced by stars more massive than about 18 $\mathfrak{M}_\odot$; nevertheless, a more precise determination of the location of the known Type Ib SN relative to H II regions is needed to reach a more firm conclusion (Wheeler 1991); and (d) it is expected that about half of the O stars will explode as SN inside H II regions.

Rosa & Mathis 1987 have found an O/H rich region inside 30 Doradus that they attribute to mass loss from a massive star inside the nebula.

Many giant H II regions show line profiles that indicate supersonic velocities (e.g., Meaburn 1984; Iye, Ulrich & Peimbert 1987; Castañeda, Vilchez & Copetti 1990a,b).

There are many extended emission-line regions around active galaxies with very high [O III] $I(\lambda4363)/I(\lambda5007)$ ratios (Tadhunter, Robinson & Morganti 1989). Even if some of them could be explained by photoionization models deficient in O/H, there are others that cannot because they show very high $I(\lambda4363)/I(\lambda5007)$ ratios and high $I(\lambda5007)/I(\mathrm{H}\beta)$ ratios at the same time. In all cases the very high $I(\lambda4363)/I(\lambda5007)$ ratios could be explained by a shock-wave contribution to $I(\lambda4363)$.

Many H II galaxies present [S II]/Hα excesses with respect to H II region models (e.g., Peimbert & Torres-Peimbert 1991).

2.2 *Composite Models*

The emission lines of giant H II regions could be contaminated by the presence of shock waves produced by stellar winds or by SNR near to or within the region. We will analyze such an effect on the [O II] $\lambda3727$, [O III] $\lambda\lambda4363,5007$, and [S II] $\lambda6717 + \lambda6731$ line intensities relative to Hβ through the consideration of a simple model where the contribution of the emission lines from the shock waves is added to the spectrum of a "typical" H II region. This would correspond to the case of a SNR outside the H II region, but close enough to be included in the same entrance slit while observing an extragalactic H II region.

For the SNRs we have used the radiative planar shock models of Hartigan, Raymond & Hartmann 1987 with a preshock number density equal to 100 cm^{-3}, $v_0 = 200$ km s^{-1} and $E = 10^{51}$ ergs, where v_0 is the transition velocity between the energy-conserving or adiabatic phase and the momentum-conserving or snowplow phase (e.g., McCray & Snow 1979), and E is the released energy. The models assume equilibrium or self-consistent preionization of the preshock gas, neglect the preshock magnetic field, and fix the preshock temperature at 10^4 K. The logarithmic abundance ratios by number are: 12.00, 10.93, 8.52, 7.96, 8.82, 8.12, 7.52, and 7.20 for H, He, C, N, O, Ne, Mg, and S, respectively.

For the H II regions we have used model ICB2 by Stasinska 1982. This model has a star with an effective temperature of 37,500 K surrounded by a nebula with an electron density of 100 cm^{-3}. The logarithmic abundance ratios by number are: 12.00, 11.00, 8.57, 8.04, 8.83, 8.00, 7.54, and 7.20 for H, He, C, N, O, Ne, Mg, and S, respectively.

In an H II region the line intensities depend on the ionizing flux; therefore, the line intensities do not vary appreciably in time scales shorter than 10^6 years (see Table 1). On the other hand, SNRs last typically about 2×10^4 years, from the SN explosion up to the time where the line emission becomes negligible, and the line intensities vary considerably during that time.

In Figure 1 we show how the line intensities $\lambda\lambda3727$, 4363, 5007, and 6724 (6717 + 6731) vary in a time scale of $\sim 2 \times 10^4$ years for a composite model made of 1 SNR and 100 O stars relative to an H II region model made of 100 O stars. The $\lambda3727$ and $\lambda5007$ intensities are almost not affected, the $\lambda6717 + \lambda6731$ intensities are mildly affected, while the $\lambda4363$ intensity is strongly affected. We will analyze how these changes affect the determination of the derived T_e and O abundances.

The electron temperature of an H II region derived from the auroral ($\lambda4363$) and the nebular ($\lambda5007$) lines of [O III] is obtained from (e.g., Osterbrock 1989)

$$\frac{I(\lambda4959) + I(\lambda5007)}{I(\lambda4363)} = \frac{7.73 \exp(3.29 \times 10^4/T_e)}{1 + 4.5 \times 10^{-4}(N_e/T_e^{1/2})}, \quad (1)$$

where $I(\lambda5007)/I(\lambda4959)$ is 2.88 (Nussbaumer & Storey 1981). Based on equation (1), in Figure 2 we show the ratio of the temperature derived from composite models relative to that of the H II region models.

Based on $T_e(\lambda4363/\lambda5007)$ and the atomic parameters for O^+ and H^0 (Pradhan 1976; Zeippen 1982; Hummer & Storey 1987) we present in Figure 3 the ratios of the derived $N(\mathrm{O}^+)/N(\mathrm{H}^+)$ abundances from the composite models relative to the H II region models. Similarly, based on $T_e(\lambda4363/\lambda5007)$ and the atomic parameters of

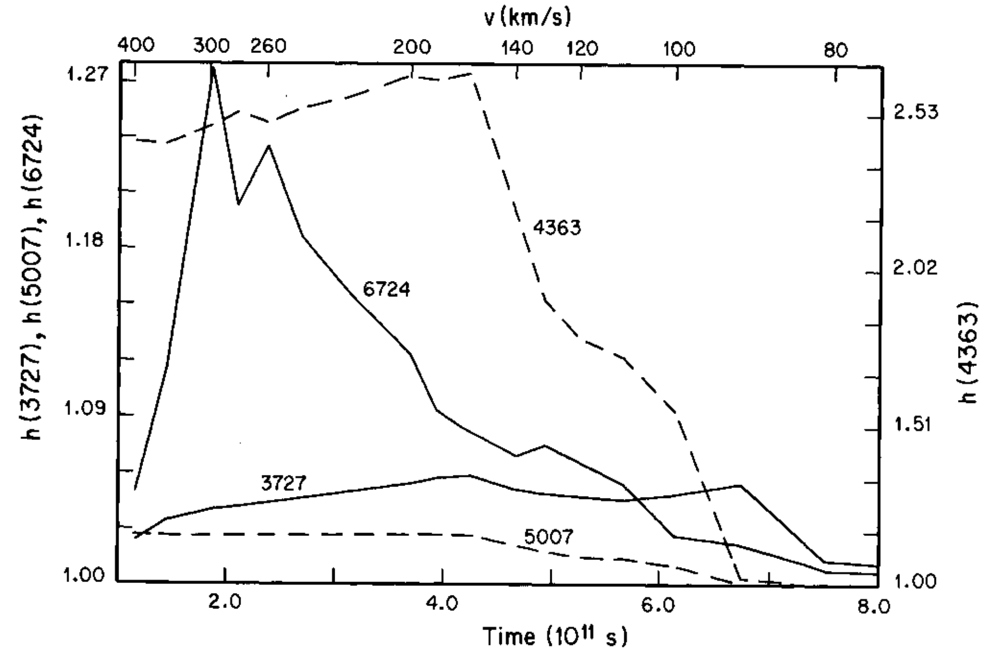

FIG. 1–Comparison of the line intensities in a composite model, made of 100 O stars and one SNR, with an H II region model made of 100 O stars. The low horizontal axis gives the time after the SN explosion; the upper horizontal axis gives the shock velocity of the SNR and $h = I$(composite)/I(H II region).

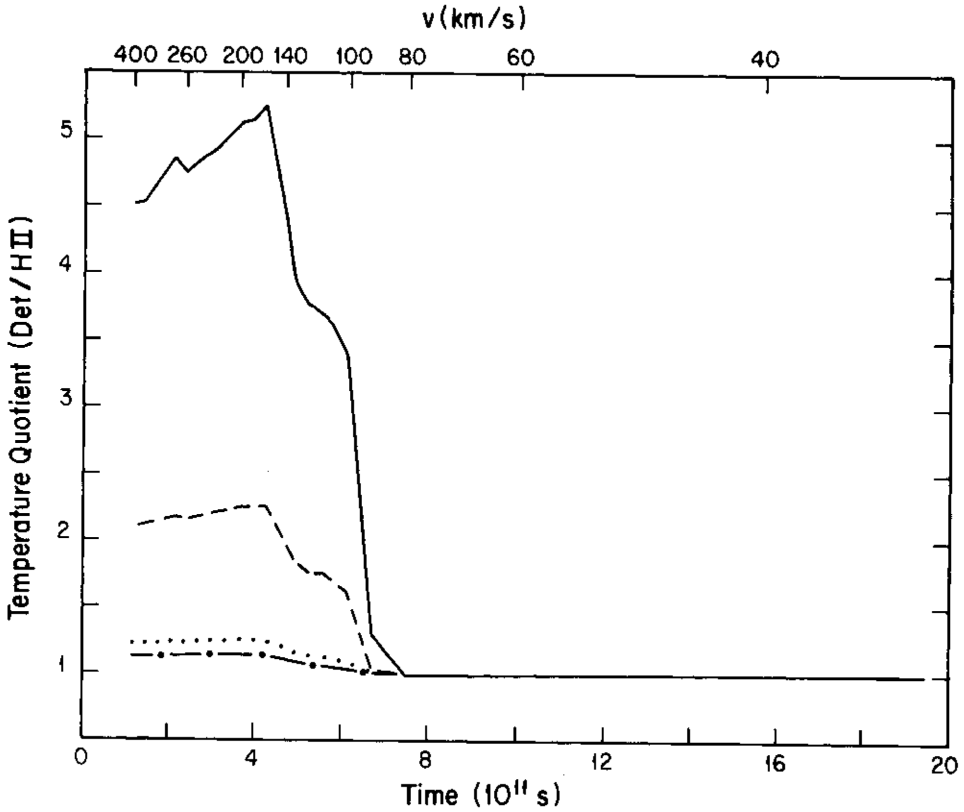

FIG. 2–Temperature quotient, derived from the $I(\lambda4363)/I(\lambda5007)$ ratios, given by $TQ = T_e$(composite)/T_e(H II). Solid line (1 SNR + 1 O star)/1 O star; dashed line (1 SNR + 10 O stars)/10 O stars; dotted line (1 SNR + 100 O stars)/100 O stars; dashed-dotted line (1 SNR + 200 O stars)/200 O stars. Horizontal axis as in Figure 1.

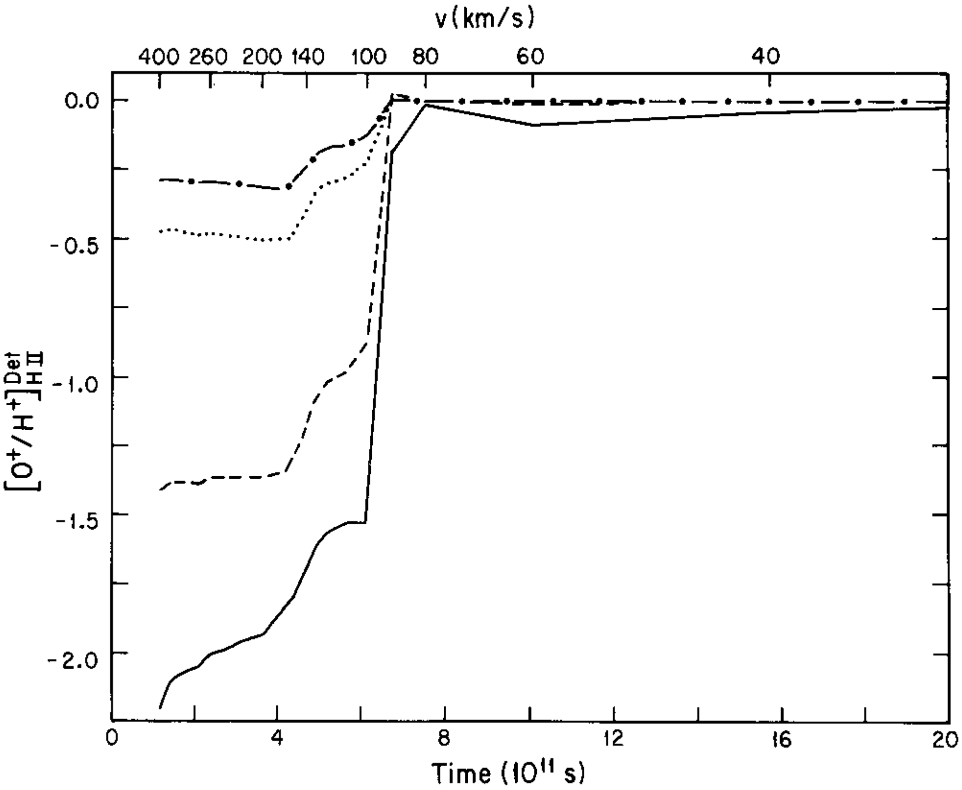

FIG. 3–Comparison of the $N(O^+)/N(H^+)$ abundances derived from the composite models with those derived from the H II region models. The abundances are obtained from T_e (λ4363/λ5007); $[O^+/H^+]^{Det}_{H\,II}$ – log $[N(O^+)/N(H^+)]_{composite}$ – log $[N(O^+)/N(H^+)]_{H\,II}$. Lines as in Figure 2.

O^{++} and H^0 (Nussbaumer & Storey 1981; Aggarwal 1983; Hummer & Storey 1987), we present in Figure 4 the $N(O^{++})/N(H^+)$ ratios. Note that even for the model of 1 SNR, for each 200 O stars we obtain a deficiency in the O^+/H^+ and O^{++}/H^+ ratios of ~ 0.3 dex relative to the real value; the effect is due to the higher T_e(λ4363/λ5007) value of the composite model relative to the H II region model.

The difficulty of measuring I(λ4363) (or any other direct temperature indicator) led Pagel et al. 1979 to propose an empirical method based on the ratio of the nebular oxygen lines to Hβ, ([O II] λ3727 + [O III] λλ4959,5007)/Hβ, to determine T_e and the O/H ratio. Based on Pagel's method, in Figure 5 we present the ratio of the derived N(O)/N(H) abundance from the composite model to that derived from the H II region model. Note that the differences are negligible because I(λ3727) and I(λ5007) are almost unaffected by the SNR contribution.

It is also possible to evaluate the effect on I(λ4363) if we assume that at each shock velocity 1% of the Hβ flux is due to shock waves and 99% to the H II region. The increase of I(λ4363) in the composite models relative to the H II region models is considerable for velocities above 90 km s^{-1}; see Figure 6.

The effect of using SNR models with "depleted" chemical abundances by Hartigan et al. 1987, instead of those with solar abundances, is almost negligible since the energy radiated by the SNR per unit time changes by factors of 1.0, 1.1, 1.1, and 1.0 for I(Hβ), I(λ3727), I(λ4363), and I(λ5007), respectively. A similar result is obtained from the computations by Raymond 1979 and Shull & McKee 1979 by changing the field strength from 1 to 10 μG.

In addition to the kinetic energy input due to SN explosions, H II regions have the kinetic energy input due to stellar winds of O stars and W-R stars. Recent estimates indicate that an O star injects approximately 10^{51} ergs of kinetic energy to the interstellar medium during its lifetime and that a W-R star does the same (Bieging 1990 and references therein). The lifetimes of O stars, W-R stars, and SNRs are several times 10^6, 10^5, and 10^4 years, respectively. Consequently, a giant H II region with several thousand O stars will have similar amounts of kinetic energy injected by O stars, W-R stars, and SNRs. H II regions with fewer O stars might or might not have a SNR inside them, but at least they will have the contribution to the kinetic energy due to the stellar winds of O stars.

In the composite models discussed in Figures 1–6 it has been assumed that the SNR is outside the H II region; therefore, shock velocities higher than 90 km s^{-1} are needed to produce O^{++} and consequently to affect I(λ4363) (see Fig. 6). Alternatively, for SNRs inside the H II region, and for shocks produced by stellar winds of O stars and W-R stars inside the H II region, shock veloc-

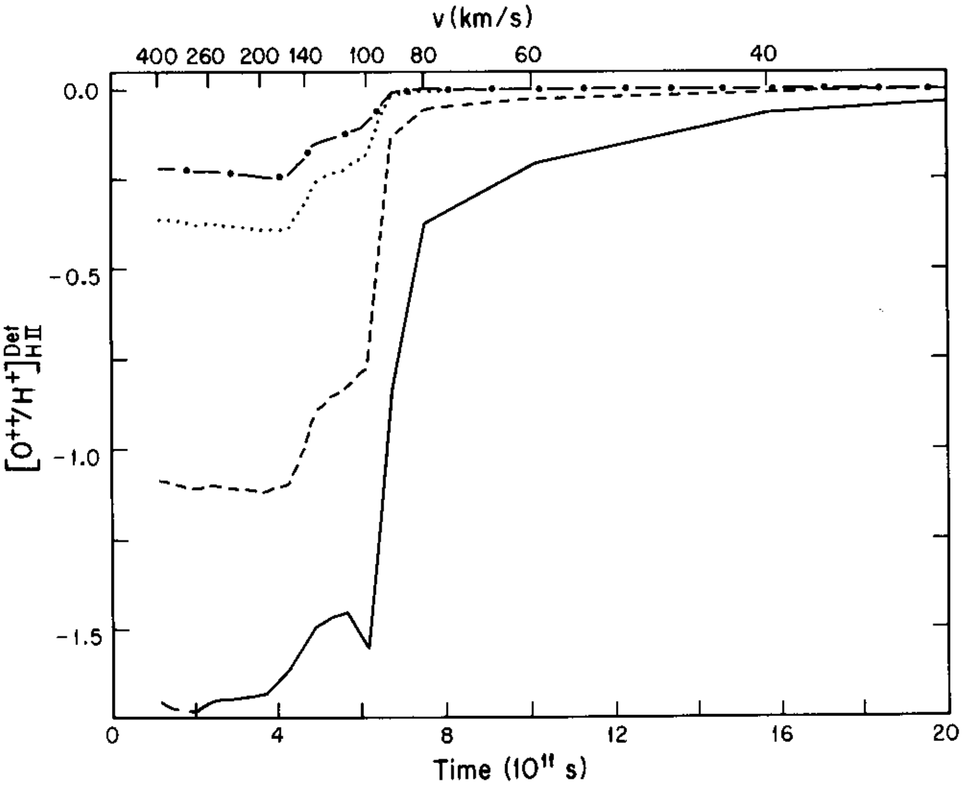

FIG. 4–Same as Figure 3 but for $N(O^{++})/N(H^{+})$.

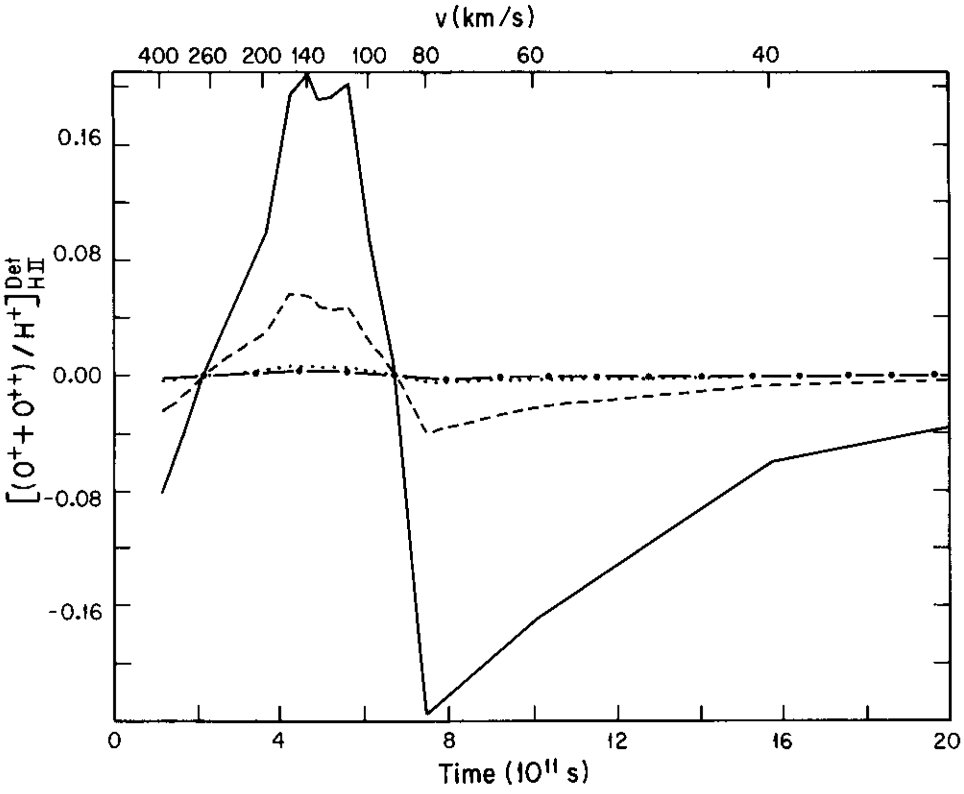

FIG. 5–Comparison of the $N(O)/N(II)$ abundances derived from the composite models with those derived from the H II region models. The abundances are determined from Pagel's method. Lines as in Figure 2.

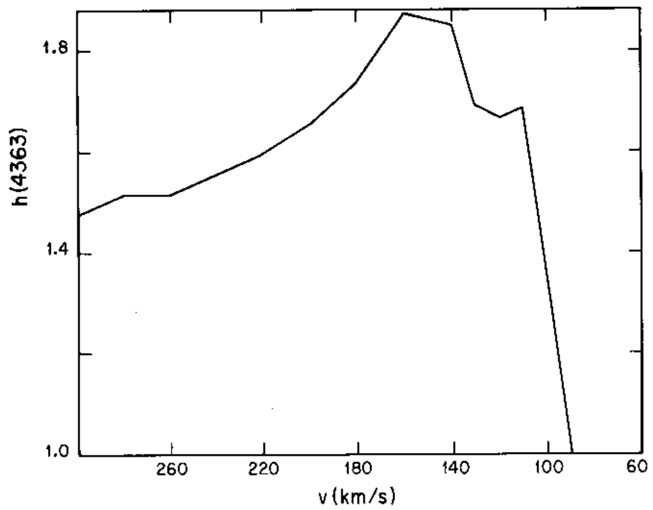

FIG. 6–Comparison of $I(\lambda 4363)$ between composite models and H II region models. In the composite models 1% of the Hβ flux is due to the SNR and 99% to the H II region; at a given velocity the H II region model and the composite model have the same Hβ flux.

ities as small as 30 km s^{-1} will considerably increase $I(\lambda 4363)$ because the O^{++} region could be produced by the stellar radiation field; the end result would be the overestimation of $T_e(\lambda 4363/\lambda 5007)$ and the underestimation of the O/H abundances at considerably smaller shock velocities than 90 km s^{-1}. The presence of a stellar radiation field in the shocked region can prevent the existence of a full recombination region and the expected [N II], [S II], and [O I] emission lines could be considerably weaker than those of a shock without a stellar radiation field.

2.3 *I Zw 18*

The N/O ratio for I Zw 18 is considerably higher than that expected from its O/H ratio (Dufour, Garnett & Shields 1988). Skillman et al. 1988 find that in the O/H versus total mass diagram I Zw 18 lies well below the relationship derived by Talent 1980; even if the mass determined by Lequeux & Viallefond 1980 were reduced by a factor of three it would still be higher, by an order of magnitude, than that predicted from Talent's relationship.

The ring-shaped structure of the NW emission complex (Davidson, Kinman & Friedman 1989) and the broad velocity component detected by Skillman 1991 argue in favor of a contribution due to shocks. On the other hand, Skillman does not find a broad component in the SE region but finds a similar O/H ratio to that of the NW region. The [O I] and [S II] lines from the NW regions are weak and argue against a shock component; nevertheless, if there is a strong stellar radiation field it could prevent the formation of a complete recombination zone.

If there is a shock component to the spectrum of the NW region the derived O/H ratio would increase and the N/O ratio would decrease because N/H does not depend as much on the adopted T_e as O/H does. These changes would bring closer the I Zw 18 value to the relationship defined by other extragalactic H II regions in the N/O versus O/H diagram. A similar situation would occur in the O/H versus total mass diagram.

3. Galactic H II Regions

Evidence for the presence of shocks in shell nebulae around luminous Population I Wolf-Rayet, Of, and P-Cygni stars has been presented by Dufour 1989 (and references therein). Dufour discusses NGC 7635, NGC 6888, and NGC 2359 where shocks with velocities in the 30 to 100 km s^{-1} range are presented. Clayton 1990 presents observations of the λ5007 line in NGC 3603, which shows a profile with wings extending from −100 km s^{-1} to 150 km s^{-1}.

There is a large body of evidence for high-velocity components in the Orion nebula (e.g., Castañeda 1988 and references therein). In addition, Castañeda & O'Dell 1987 and Castañeda 1988, from the study of the λ5007 velocity profile in 992 positions of the central regions of the Orion nebula, have found three velocity components: components A and B that were already known and that show a nonthermal component smaller than the sound velocity, and component C, detected in 925 positions with an average FWHM of 31.26 ± 0.21 km s^{-1} where the thermal component is larger than the sound velocity and that could indicate the presence of shock waves. From high-resolution radio continuum images of the Orion nebula and after enhancing the sharp features, by suppressing the smooth contribution close to them, Yusef-Zadeh 1990 has found stringlike features that he argues might be due to shock fronts inside the nebula.

A different type of observational evidence in favor of the presence of shock waves is based on the determination of the average temperature, T_0, and the root-mean-square temperature variation, t, defined as follows (Peimbert 1967)

$$T_0 = \frac{\int T_e N_e N_i \, dV}{\int N_e N_i \, dV} \tag{2}$$

and

$$t^2 = \frac{\int T_e^{\,2} N_e N_i \, dV - T_0^2 \int N_e N_i \, dV}{T_0^2 \int N_e N_i \, dV} \,. \tag{3}$$

By comparing a T_e that weights preferentially high-temperature regions with a T_e that weights preferentially low-temperature regions it is possible to determine T_0 and t^2; for example, T_e (λ4363/λ5007) and T_e derived from the ratio of the Balmer continuum to Hβ, T_e (Bac/Hβ), are given by Peimbert 1967

$$T_e\,(\lambda4363/\lambda5007) = T_0\left[1 + \frac{1}{2}\left(\frac{90800}{T_0} - 3\right)t^2\right] \quad (4)$$

and

$$T_e\,(\text{Bac/H}\beta) = T_0\,(1 - 1.70\,t^2)\ . \quad (5)$$

From T_e (λ4363/λ5007), T_e (λ5755/λ6583), T_e (Bac/Hβ), and T_e (radio) values in the $0.015 \le t^2 \le 0.055$ range for the Orion nebula have been found (Peimbert 1967; Peimbert & Costero 1969; Torres-Peimbert, Peimbert & Daltabuit 1980 and references therein). Recent determinations for M 8 are in the $0.017 \le t^2 \le 0.051$ range (see Table 2).

Torres-Peimbert et al. 1980 adopted a t^2 value of 0.02 for the Orion nebula based on the C^{++} abundances derived from the collisionally excited lines of [C III] and C III] at λ1907 and λ1909 and the recombination lines of C^+ at λ4267. Walter 1991 derives C^{++} abundances a factor of 0.2 dex smaller based on the λ1907 and λ1909 lines; his result is obtained from a different extinction law, a reanalysis of all the IUE data available, and newer atomic parameters. To reconcile the new C^{++}/H^+ abundances by Walter to those derived from λ4267 a value of $t^2 \sim 0.035$ would have to be adopted.

The one-dimensional photoionized model of the Orion nebula by Simpson et al. 1986 predicts I(λ4363)I(λ5007) ratios considerably lower than observed. To reach agreement between the model and the observations, t^2 values in the 0.036 to 0.058 range are needed. Similarly, the two-dimensional blister model of the Orion nebula by Rubin et al. 1991 again predicts I(λ4363)/I(λ5007) ratios considerably smaller than observed. These differences cannot be explained by the models and indicate the presence of substantial temperature variations along the line of sight probably due to shock waves. In Table 3 we present the O/H ratio for the Orion nebula for different t^2 values (Peimbert & Torres-Peimbert 1977).

Gruenwald & Viegas 1991 have computed line-of-sight results for a large set of photoionization models. They find that, in general, it is difficult to find t^2 values larger than 0.025. In general, higher t^2 values are obtained for later-type stars and for observations closer to the central star. For integrated observations of O6 stars t^2 values are ~ 0.01. Consequently, t^2 values of ~ 0.04 cannot be explained by photoionization alone.

TABLE 2

Temperatures and Mean Temperature Variations for M8

	M8 Hourglass	⟨M8⟩
T_e (4363/5007)	8600 ± 200	7850 ± 200
T_e (5755/6583)	8450 ± 300	7950 ± 300
T_e (Bac/Hβ)	6600 ± 1000	--
T_e (radio)	---	7100 ± 400
t^2(O III)	0.044 ± 0.022	0.017 ± 0.009
t^2(N II)	0.051 ± 0.028	0.025 ± 0.012
References	1	1,2,3

1-Sanchez & Peimbert 1991; 2-Peimbert & Costero 1969; 3-Rodríguez & Lichten 1979.

TABLE 3

Oxygen Abundances for the Orion Nebula

t^2	12 + log N(O)/N(H)
0.00	8.52
0.02	8.65
0.035	8.75
0.055	8.92

4. Planetary Nebulae

The central stars of PN are losing mass at velocities in the 1000 to 4000 km s^{-1} range. This stellar wind interacts with material that was ejected previously at about 20 km s^{-1} producing shocks (e.g., Kahn 1989; Balick 1989, and references therein).

Most PN show expansion velocities of the shell in the 20 to 30 km s^{-1} range. There is a group of PN of Type I that shows considerably higher velocities of expansion. The [Ne V] line at λ3426 of NGC 6302 shows an 800 km s^{-1} wide component (Meaburn & Walsh 1980). The velocity field of He2-111 resembles that of NGC 6302 (Webster 1978). NGC 2899 shows high-velocity features reaching −130 km s^{-1} in the equatorial condensations and +110 km s^{-1} in the NW lobe (López et al. 1991). The low surface brightness outer lobes of NGC 2440, Mz-3, and Hu1-2 show expansion velocities in excess of 70 km s^{-1} (Weller & Heathcote 1989; Sabbadin, Cappellaro & Turatto 1987).

Middlemass, Clegg & Walsh 1989, 1991 and Manchado & Pottasch 1989 have reported for the large faint halos of several PN high T_e values and apparently low O/H ratios in comparison with the central brighter parts. Middlemass et al. 1991 interpret these results in terms of shocked filamentary regions, with the energy input coming from the winds produced by the central stars; the faint outer halo of NGC 7662 shows an apparent O/H ratio a factor of two smaller than that of the inner bright core.

Dinerstein, Lester & Werner 1985 (see also Dinerstein 1986, 1990), from the [O III] lines at λλ4363,5007, 52 μm and 88 μm, determined T_0, N_e, and t^2 at the same time for six PN. In particular they showed that

$$T_e\,(\lambda4363/\lambda5007) \approx T_e\,(\lambda5007/52\,\mu\text{m})\,(1 + 3\,t^2)\ ; \quad (6)$$

the $\langle t^2 \rangle$ value for the six objects is 0.04, which produces $N(O^{++})/N(H^+)$ values from 0.2 dex to 0.3 dex higher than the isothermal value. Alternatively, Harrington et al. 1982 have found for photoionized models of high-ionization nebulae, with a He^{++} zone, t^2 values of 0.02 or less, while for nebulae without a He^{++} zone the t^2 values are even smaller. Therefore, to explain t^2 values as high as 0.04 an additional source of energy is needed.

5. Discussion and Conclusions

A considerable fraction of SN of Types II and Ib explode inside and near H II regions; consequently, the spectra of H II regions might be contaminated by shock waves.

Stellar winds from O stars and W-R stars of Population I and from the central stars of PN also produce shock waves.

The main effect of the shock waves is to increase the intensity of the auroral lines. In particular, they increase the $I(\lambda4363)/I(H\beta)$ ratio but leave the $I(\lambda3727)/I(H\beta)$ and $I(\lambda5007)/I(H\beta)$ ratios almost unaffected. By assuming that T_e is given by the $I(\lambda4363)/I(\lambda5007)$ ratio the O/H ratio is underestimated, the N/H ratio is underestimated by a smaller amount, and the N/O ratio is overestimated.

There are significant differences between the calibrations of Pagel's method to determine O/H ratios for extragalactic H II regions based on models (McCall, Rybski & Shields 1985; Dopita & Evans 1986; McGaugh 1991) and the calibrations based on observations (Edmunds & Pagel 1984; Torres-Peimbert et al. 1989). The differences are in the 0.2 dex to 0.4 dex range and could be due to the presence of temperature inhomogeneities over the observed volumes (Torres-Peimbert et al. 1989; McGaugh 1991). The differences imply t^2 values around 0.04 for H II regions with solar O/H ratios. These large t^2 values could be due to shock waves. Since Pagel's method is not affected by shock waves it is an excellent tool to determine O/H ratios, but it has to be calibrated from models and not from observations. The observations could be used to calibrate Pagel's method if the temperature structure of the nebulae were known.

The large t^2 values derived for Orion and M 8 and the high $I(\lambda4363/I(\lambda5007)$ ratios observed in Orion cannot be explained by photoionized models; shock-wave dissipation might be responsible for them.

Large t^2 values, of the order of 0.04, produce agreement between the O/H ratios of PN and those of Population I stars (Dinerstein et al. 1985). The lower C^{++} abundances derived from the $\lambda1907 + \lambda1909$ lines also support an increase of the t^2 value for the Orion nebula, bringing closer together the O/H ratios of the Orion nebula and the Sun (e.g., Peimbert 1987 and Table 3 of this article).

The presence of SNR outside H II regions would help to explain the large [S II]/Hα ratios observed in some H II galaxies.

The low O/H values and the N/O versus O/H anticorrelation present in some Type I PN (Peimbert & Torres-Peimbert 1983; Peimbert 1990 and references therein) could be partly due to shock waves. Part of the anticorrelation could be due to the transformation of O into N; nevertheless, the most favorable stellar evolutionary models predict depletions of O of a factor of 1.4 (Renzini & Voli 1981; Renzini 1984), while the observed O depletion in some of the extreme cases reaches factors of 2 to 3.

Similarly, the N/O versus O/H anticorrelation found by Dufour 1989 for some shell nebulae ionized by Population I stars could be partly due to shock waves (Dufour 1991).

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