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LETTER

Letter to the Editor

On the origin of [O IV] emission in Wolf-Rayet galaxies

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Abstract. We propose that the emission of the high excitation [O IV] 25.9 μm line observed with ISO in NGC 5253 and II Zw 40 is due to the presence of hot Wolf-Rayet (WR) stars in these objects. We construct a consistent evolutionary synthesis and photoionization model which successfully reproduces the constraints on their massive star content and the relevant optical and IR emission lines including [O IV] 25.9 μm. Our explanation for the origin of [O IV] is supported empirically by: *1)* the simultaneous presence of nebular He II and [O IV] in these objects, and *2)* the close relation between nebular He II and WR stars in extragalactic HII regions. Photoionization by hot WR stars is mainly expected to be of importance in young low metallicity galaxies. Alternate mechanisms are likely at the origin of [O IV] 25.9 μm emission in other objects.

Key words: galaxies: starburst – galaxies: stellar content – ISM: H II regions – stars: Wolf-Rayet – infrared: galaxies – galaxies: individual: NGC 5253 – galaxies: individual: II Zw 40

1. Introduction

Infrared observations of emission line galaxies give access to ions not visible in the optical domain. Among those is the high excitation [O IV] 25.9 μm line which has not only been observed in active galactic nuclei but also in several starburst galaxies, although at a much fainter level (Genzel et al. 1998, Lutz et al. 1998, hereafter LKST98).

Hot, massive stars generally emit only few ionizing photons with energies above the He II edge at 54.42 eV required for the production of [O IV]. Therefore the origin of this high excitation line in starbursts has been unclear so far. Different excitation mechanisms (weak AGNs, super-hot stars, planetary nebulae, and ionizing shocks) have been discussed by LKST98. Based on simple estimates, photoionization and shock models, these authors favor ionizing shocks related to the starburst activity as the most likely explanation for [O IV] 25.9 μm emission *in general*.

According to LKST98, massive super-hot stars remain, however, an option for the high excitation dwarf galaxies included in their sample. One of these objects (NGC 5253) was studied in more detail by Crowther et al. (1999, hereafter C99), who showed, by computing photoionization models around single stars, that WNE-w stars can indeed produce strong [O IV] and [Ne V] in surrounding HII regions. The fact that these lines were not prominent in NGC 5253 led them to exclude the possibility of a significant number of such stars being present in this galaxy. As will be shown below we do not support their conclusion for a variety of reasons.

To shed more light on the origin of the [O IV] 25.9 μm emission in dwarf galaxies, we use the information on nebular properties and stellar content derived from optical studies to complement the information from IR data. In addition to NGC 5253, we also consider II Zw 40. These are the two compact low metallicity galaxies which show the highest excitation among the starbursts observed by LKST98. Both objects are known as so-called WR galaxies (cf. Conti 1991, Schaerer et al. 1999b), where the presence of broad stellar emission testifying to the presence of WR stars provides powerful constraints on the burst age and massive star content (e.g. Schaerer et al. 1999a).

In this paper, we present a stellar population model which reproduces the observed stellar features and which, used as an input for photoionization models, explains at the same time the ionization structure of the nebular gas as revealed by the optical and IR fine structure lines.

2. On the association of [O IV] 25.9 μm with He II

In the sample of [O IV] emitting starbursts of LKST98, II Zw 40 and NGC 5253 show the strongest excitation (measured by [Ne III]/[Ne II]), the largest [O IV] strength (quantified by [O IV]/([Ne II]+0.44[Ne III]); cf. LKST98, Fig. 2) and stand out by several properties:

1) Nebular He II λ4686 emission indicative of high excitation is present in the region dominating the optical emission (Walsh & Roy 1989, 1993, hereafter WR89, WR93, Guseva et al. 1998)

2) A significant number of Wolf-Rayet stars has been detected in these regions (Kunth & Schild 1981, Walsh & Roy 1987, Vacca & Conti 1992, Schaerer et al. 1997, hereafter SCKM97)

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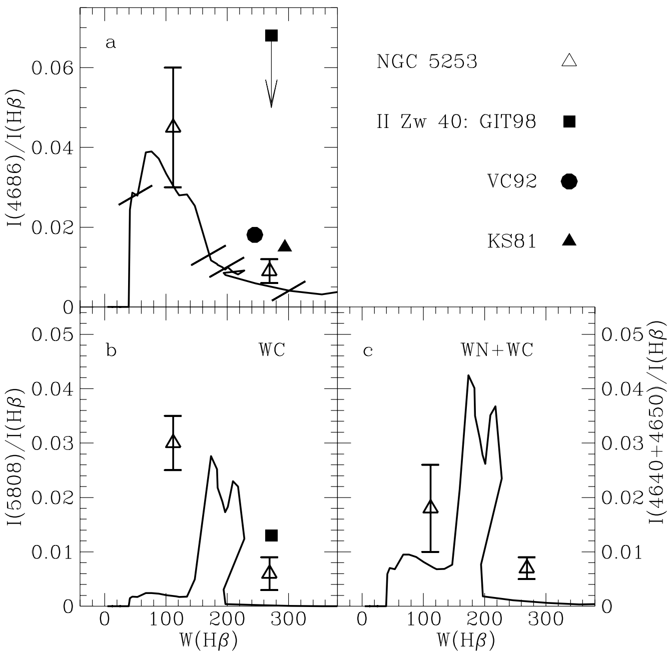

Fig. 1a–c. Observed and predicted WR lines intensities as a function of $W(\mathrm{H}\beta)$: broad He II λ4686 **a**, C IV λ5808 **b**, and N III λ4640+ C III λ4650 **c**. Model predictions for an instantaneous burst with a Salpeter IMF for Z=0.004. Observational data from: NGC5253 – regions A and B from Schaerer et al. (1999a), II Zw 40 – data from Kunth & Schild (1981), Vacca & Conti (1992) and Guseva et al. (1998). Tickmarks in a) represent ages of 2.8, 3.0, 4.2, and 5.0 Myr respectively. The observed WR and O star populations are well reproduced for burst ages of ∼ 3–5 Myr.

3) In both the dwarf II Zw 40 and the amorphous galaxy NGC 5253 one or few star forming regions of a young age clearly dominate the production of ionizing photons (Vanzi et al. 1996, Beck et al. 1996, Calzetti et al. 1997).

Finding 1) confirms the presence of high energy photons ($>$ 54 eV) deduced from the IR observations of [O IV] and naturally suggests a direct link between the nebular He II and [O IV] emission. Furthermore the optical observations allow a more precise localisation of the high excitation regions. 1) and 2) indicate that II Zw 40 and NGC 5253 are objects where the observed He II emission is likely due to hot WR stars (Schaerer 1996, 1997, 1998; De Mello et al. 1998). 3) justifies, at least to first order, the use of a “spectral template” of the brightest starburst region as a representation of the ionizing spectrum of the entire region covered by the ISO observations.

3. Stellar population

WR stars of both WN and WC types have been observed in the two dominant regions of NGC 5253 by SCKM97. In II Zw 40 broad He II λ4686 indicative of WR stars was detected by Kunth & Sargent (1981), Vacca & Conti (1992) and Guseva et al. (1998). The latter also detect broad C IV λ5808 emission due to WC stars. The WR and O star content was already analysed by Schaerer (1996), SCKM97 and Schaerer et al. (1999a). In Fig. 1 the observed intensities of the various WR features are shown and compared to an instantaneous burst model of Schaerer & Vacca (1998) with a Salpeter IMF at the appropriate metallicity ($Z/Z_\odot \sim$ 1/5). The observations of Guseva et al. (1998) refer to the entire “WR bump” (4643–4723 Å) and represent therefore an upper limit. Shifts in $W(\mathrm{H}\beta)$ of the theoretical predictions for the WC lines with respect to the observations are not significant since they correspond to very short timescales. This and other potential uncertainties affecting such a comparison have been extensively discussed in Schaerer et al. (1999a). Fig. 1 shows that all line strengths are reasonably well reproduced by the model. At the corresponding ages of ∼ 3–5 Myr (cf. SCKM97) our synthesis model provides therefore a good description of the massive star content in these regions.

4. Photoionization models

The spectral energy distributions predicted by the synthesis models described above have been used as input to the photoionization code *PHOTO* (same version as in Stasińska & Leitherer 1996, hereafter SL96). The remaining input parameters are the total number of stars, the density distribution and the chemical composition here taken as $Z/Z_\odot$=1/4 for easy comparison with SL96 (the ionization structure of a nebula is insensitive to a small change in the abundances in the gas). Following SL96 we calculate sequences of models for a spherical gaz distribution with a uniform hydrogen density n and filling factor ϵ, both assumed constant during the evolution of the starburst. For a given age, models with the same ionization parameter $U = A(Q_{\mathrm{H}^0} n \epsilon^2)^{1/3}$ have the same ionization structure. Q_{H^0} is the total number of photons above 13.6 eV, and A a function of the electron temperature (see SL96). The densities derived in II Zw 40 and NGC 5253 (∼ 70–300 cm^{-3}, WR89, WR93, C99) are low enough, so that collisional deexcitation is negligible for the lines of interest. We therefore explore the parameter space by simply taking n=10 cm^{-3} and ϵ=1, and consider three different initial masses for the starburst: 10^3, 10^6 and 10^9 $M_\odot$. These three model sequences will be referred to as the sequence with low, intermediate and high U.

In Fig. 2 we show the temporal evolution of selected line ratios. Unlike C99, we chose to show line ratios that are independent of the abundances of the parent elements, in order to facilitate comparison with observations of different galaxies. The only exceptions are [O IV]/[Ne III] [1] and He I λ5876/Hβ when helium is fully ionized in the HII region. Also, we limit ourselves to line ratios that involve a dominant ionic stage in the nebula. Line ratios like [O IV] 25.9 μm/[Ne II] 12.81 μm or [Ne V] 14.3 μm/[Ne II] 12.81 μm as used by Genzel et al. (1998) are difficult to interpret, as the lines are likely emitted by very different regions.

As expected, line ratios from adjacent ionic stages show a progressive decrease of the overall excitation with time for the models we are considering. Helium remains fully ionized up to 4 Myr. Notable exceptions to this trend are [O IV], [Ne V] and

[1] The O/Ne ratio is 5.0 in the models compared to 4.9–5.5 in II Zw 40 (WR93) and 4.–7.4 in NGC 5253 (WR89).

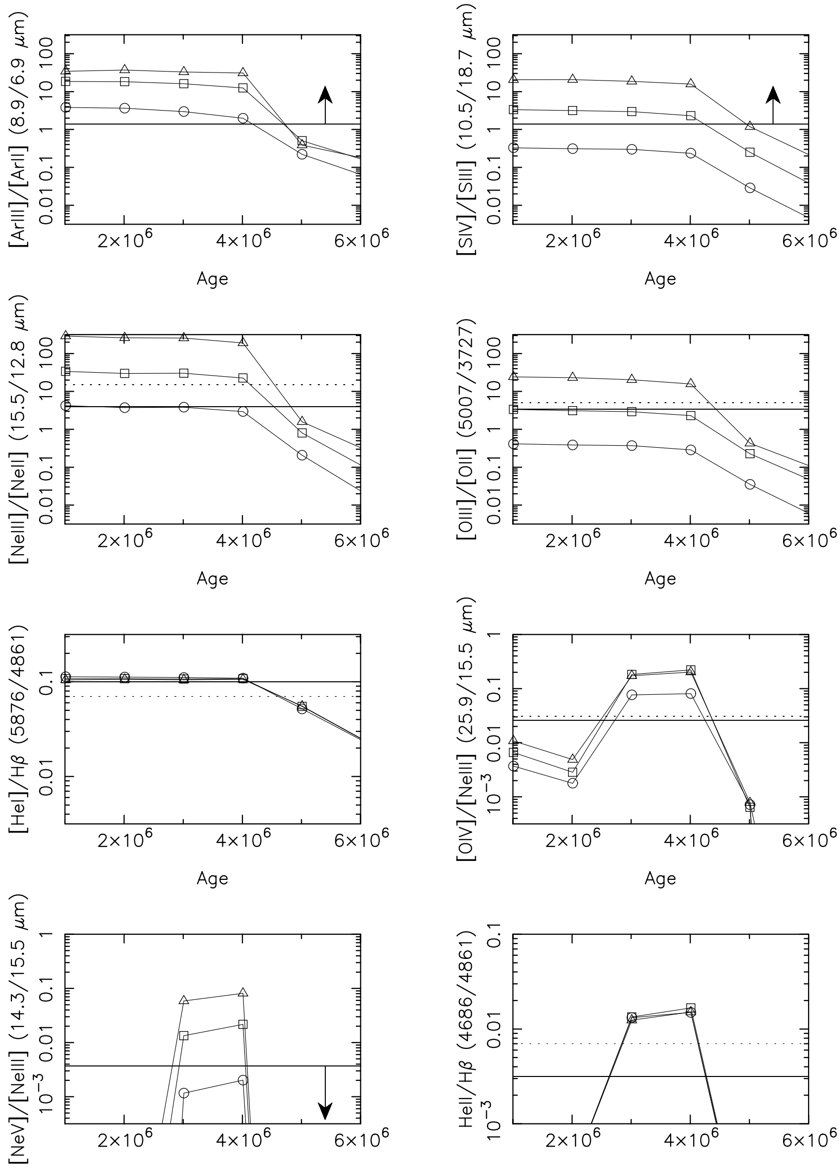

Fig. 2. Comparison of observed and predicted IR and optical line ratios for instantaneous burst models as a function of time. *Models:* Circles denote low U models, squares intermediate U, triangles high U models. Filled spheres with $n = 10\,\mathrm{cm}^{-3}$. *Observations:* NGC 5253 – solid lines, II Zw 40 – dotted lines. Sources given in text.

He II, species with the ionization potential at or above the He II edge, which appear during a short phase (at ages $t \sim$ 3–4 Myr) where hot WR stars provide a non-negligible flux above 54 eV (see Schaerer & Vacca 1998). Slower temporal changes would of course be obtained for non instantaneous bursts.

It must be noted that those line ratios which are function of the ionization parameter also depend somewhat on the adopted geometry, and this in a non trivial way. For example, in models with a thin shell geometry, the line ratios shown here differ by factors up to 3 from models for full spheres with the same mean ionization parameter. In the case of the [Ne V]/[Ne III] ratio, the value predicted during the WR phase can be smaller by a factor of about 10 since, despite the presence of high energy photons, there is no matter emitting at a high ionization parameter, close to the star cluster.

In the following we compare the model predictions with observations of NGC 5253 and II Zw 40.

5. Comparison with observations of NGC 5253 and II Zw 40

Observed line ratios are overplotted on the model predictions shown in Fig. 2. The optical data is taken from WR89 and WR93 (region 1 in both objects). IR fluxes for NGC 5253 are taken from Genzel et al. (1998), LKST98, and C99. For [S IV]/[S III] a lower limit is obtained since different ISO apertures are involved in the measurements. All other limits are "real" detection limits. Adopting the Draine (1989) extinction curve and $A_v = 7.7$ mag (C99) increases the [Ar III]/[Ar II] and [S IV]/[S III] ratios by $\sim$ 40%. Other IR line ratios are much less affected. C99 consider two separate emission regions to be responsible for the high excitation lines (e.g. [S IV]) and lower excitation lines respectively (e.g. [Ne II]). We see no compelling reason for such a somewhat "artificial" separation. A similar structure is e.g. naturally obtained in an ideal spherical nebula. Instead of using line fluxes corrected for such effects we therefore use the original measurements. IR line ratios for II Zw 40 are from LKST98. We have no access to the acquired ISO SWS spectra, which should, however, become available soon.

From the top panels of Fig. 2 it is evident that no single model can reproduce at the same time all the observed line ratios. This finding is not surprising and may be due to several reasons: 1) The structure of the galaxies is more complicated than assumed in the models. 2) Although one or few bursts of similarly young age dominate the ionizing flux (Sect. 2), the ionizing spectrum is likely not fully described by a single burst population. 3) Atomic data may be inaccurate. In particular, the computation of collision strenghts for fine structure transitions is a very delicate problem, and the evaluation of the formal uncertainty is difficult. A comparison between the plasma diagnostics obtained using different IR and optical lines for the planetary nebula NGC 6302 led Oliva et al. (1996) to suggest that the collision strengths which enter in the calculation of the intensity of [Ne V] 14.3 μm are overestimated by a factor 3! Similar problems are likely to occur for other fine structure lines.

The [O III]/[O II] ratio, which is one of the best studied from all points of view, indicates that, if the age of the starburst lies between 3 and 4 Myr, as indicated by the Wolf-Rayet features, the models with intermediate U are the most adequate to represent the two galaxies under study. At such an age, helium is still completely ionized, because the radiation field is hard enough. The discrepancy with the measurement of He I λ5876/Hβ in II Zw 40 is likely due to absorption by Galactic interstellar sodium intervening at this redshift (Izotov 1999, private communication).

Our main result is illustrated in the last three panels of Fig. 2 where we show that during a short phase the stellar population provides enough photons above 54.4 eV to naturally produce the He II λ4686, [O IV] and [Ne V] lines at levels comparable to the observed ones. The emission is due to the presence of hot WR stars at ages $t \sim$ 3–4 Myr (cf. Schaerer 1996, Schaerer & Vacca 1998). The predicted strength of these lines exceeds even somewhat the observations[2]. However, this does not invalidate our conclusion. A more realistic population "mix" can easily reconcile the intensity of He II λ4686 with the observations. As for the [O IV] and [Ne V] lines, they are sensitive to the geometry (see above), which provides ample space for fitting with tailored photoionization models. This should, however, only be undertaken when the relevant atomic data have been validated by detailed multiwavelength studies of simpler objects and by comparisons with photoionization models.

6. Summary and discussion

We propose that [O IV] 25.9 μm emission in NGC 5253 and II Zw 40 is due to the presence of hot WR stars observed in both objects. We draw this conclusion from both empirical and theoretical facts. First, we note that nebular He II λ4686 and [O IV] emission occur simultaneously in these objects. Furthermore a close link between nebular He II and WR stars has now been established for the so-called WR galaxies, extra-galactic H II regions and the few Local Group H II regions exhibiting this feature (Schaerer 1996, 1997, 1998; see Schaerer et al. 1999b for a catalogue of these objects). Second, quantitative models of the stellar populations using up-to-date non-LTE atmospheres including stellar winds and the most recent evolutionary tracks are able to explain the observed massive star population and the optical emission lines (including nebular He II λ4686) during the WR rich phase (Schaerer 1996, 1998), even for the lowest metallicity object, I Zw 18 (De Mello et al. 1998, Stasińska & Schaerer 1999), where such stars were detected recently. In addition, as demonstrated here, the [O IV] emission (and other IR lines) is also naturally reproduced by these models. The two objects considered here are the best available to constrain the origin of [O IV] emission: they show the highest excitation, and represent the most simple objects in terms of their ionizing population.

IR observations of the 8 Local Group (LG) H II regions known to exhibit nebular He II (cf. Garnett et al. 1991) can provide a simple "consistency" test: the presence of this line is a necessary condition for showing [O IV] emission. The presence or absence of [O IV] 25.9 μm is, however, also influenced by the ionization parameter and the nebular geometry (cf. above).

Observational evidence suggests that such high excitation H II regions occur preferentially at low metallicities. This holds both for the LG and extragalactic objects (cf. Schaerer 1997, 1998), including II Zw 40 and NGC 5253. The same can thus be expected for the contribution of WR stars to [O IV]. Low metallicity may indeed also justify the neglect of line blanketing in the WR models of Schmutz et al. (1992) included in our synthesis models. The effects discussed by C99 and Crowther (1998) suppressing the output of photons above the He II edge in metal-rich WR models and/or high density winds could well be ineffective at low metallicities, as also suggested by the empirical evidence.

Our explanation for the stellar photoionization origin of [O IV] in dwarf-like low metallicity galaxies cannot be necessarily generalised to all the objects of LKST98. Although indeed 6 out of 14 from their list are known WR "galaxies" (Schaerer et al. 1999b), it is unlikely that the regions where WR stars are detected contribute a significant fraction of the total ionizing flux in these complex objects. Outflows, weak Seyfert activity, and other phenomena are known in some of them and provide alternative explanations as discussed by LKST98. More complex models will be required to interpret such objects, to provide an theoretical understanding of new empirical IR diagnostic diagrams (cf. Genzel et al. 1998), and to assess the contribution of stellar sources to high energy photons.

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