Massive Star Forming Regions: from diagnostic tools to derived properties

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Abstract. The current state-of-the-art of multi-wavelength diagnostic tools (evolutionary synthesis, photoionisation models) for massive star forming regions (HII regions, starbursts, etc.) and some of their input physics (especially model atmospheres) is reviewed. Analysis of stellar populations based on integrated spectra from both stellar features and nebular emission lines from the UV to IR are summarised. We stress the importance of “template” studies at various scales (from individual stars to well studied galaxies) and various wavelengths, to understand the processes operating in massive star forming regions and to reliably derive their properties.

1. Introduction

In a variety of objects ranging from stellar clusters, HII regions, over dwarf and irregular galaxies, to full-fledged starburst (SB) galaxies and distant Lyman-break galaxies, massive star formation plays a major role in the budget of radiative, mechanical and chemical output. Indeed, when present, such stars (mostly OB and Wolf-Rayet stars) dominate the light at UV–optical wavelength, they are responsible for the ionisation of the ISM, and they also dominate (together with SN) mechanical feedback processes.

The present review deals with diagnostic techniques and the properties of objects of the types mentioned above, for which the “generic” term massive star forming regions (MSFR) will be used subsequently. As such we are mostly limited to objects where the properties of integrated populations (as opposed to resolved stellar populations; cf. Gallart, Grebel, these proceedings) are observed. The aim is to review the current state-of-the-art of various tools (evolutionary synthesis, photoionisation models) and some of their inputs (especially ionising fluxes), to assess their main successes and failures (and the lessons to be learned from that), and to summarise some of the main properties of stellar populations in various MSFRs.

2. Radiative output from massive stars

Schematically the main observed UV to far-IR features of integrated stellar populations can be grouped as follows:
1. **Continuum:** From the UV to \( \sim 4 \ \mu m \) (approx. L or M bands) the continuum is usually dominated by stellar light, except in very young objects (e.g. strong emission line (EL) objects) where continuous nebular emission may be non-negligible and may in particular affect observed colours. At longer wavelength dust emission usually starts to dominate the continuum emission.

2. **Stellar signatures:** Due to the increasing nebular and dust emission towards the near-IR, stellar signatures are preferentially detected at UV – optical – K band wavelengths. Among the strongest stellar features are: UV P-Cygni lines (C\(_{\text{iv}}\) \( \lambda \)1550, Si\(_{\text{iv}}\) \( \lambda \)1400, ...) emitted in the stellar winds of OB stars, broad emission lines (He\(_{\text{ii}}\) \( \lambda \)4686, C\(_{\text{iv}}\) \( \lambda \)5808) from Wolf-Rayet (WR) stars, H and He absorption lines from OBA stars in the optical, and various absorption features (e.g. Ca\(_{\text{ii}}\) triplet, TiO features in the optical, CO absorption bands in K band) from cool giants and supergiants.

3. **Nebular lines:** Relatively few and faint lines are in the UV, opposed to numerous H and He recombination lines and forbidden lines from abundant metals (N, O, S etc.) in the optical. A rich spectrum of H recombination lines and fine structure lines is observed from the near to far IR (Ne, S, Ar: \( \sim 3-40 \ \mu m \); C, N, O \( \sim 40 \ \mu m \)). The emission originates mostly from ionised gas (“H\(_{\text{ii}}\)” regions in the former case; the latter also includes lines emitted in photo-dissociation regions (PDR; e.g. [C\(_{\text{ii}}\)] 158 \( \mu m \)).

Subsequently we shall summarise the current state-of-the-art of analysis of stellar populations based on stellar signatures (Sect. 3) and through nebular lines (Sect. 4).

### 3. Starbursts in the UV and optical: stellar features

In recent years analysis of UV spectra have mostly been performed by the groups of Leitherer, Heckman, Robert, Meurer, Conti, González-Delgado and other co-workers, Mas-Hesse & Kunth and others. Most of the observations are based on HST (GHRS or STIS), HUT and IUE (FUSE data upcoming) of nearby starbursts. Restframe UV spectra of Lyman-break galaxies (e.g. Lowenthal et al. 1997, Pettini et al. 2000) now allow to extend such studies to high-redshift star forming galaxies. The Starburst99 evolutionary synthesis models (Leitherer et al. 1999) used for the interpretation of the data include for this wavelength range empirical IUE high-resolution spectral libraries of Galactic O and WR stars (+ B stars: de Mello et al. 2000); low-resolution spectra are used in the Mas-Hesse & Kunth (1999) models. Work by several groups is in progress to include libraries of low metallicity stars.

Most studies where this UV technique has been applied yield similar results which can, “on average”, be summarised as follows (e.g. González Delgado et al. 1998, Leitherer 1999b): 1) the presence of the UV wind features indicates young bursts (ages \( \lesssim 10-20 \) Myr); 2) often it is difficult to distinguish between constant SF or instantaneous bursts; 3) the observations are generally compatible with a “normal” Salpeter IMF extending to high masses (\( M_{\text{up}} \sim 60-100 \) M\(_{\odot}\)).
Extended SF and older ages are e.g. favoured for the high redshift galaxy cB58 (de Mello et al. 2000, Pettini et al. 2000). Such a difference is probably simply due a larger mixture of various regions included in the aperture for such distant an object. Some interesting extensions of the UV analysis are the potential use of wind lines to estimate the metallicity of these objects (Leitherer 1999a), and the simultaneous interpretation of interstellar lines indicative of the state of the ISM (e.g. González Delgado et al. 1998, Heap 2000).

In the optical, studies of the so-called Wolf-Rayet (WR) galaxies (see compilation by Schaerer et al. 1999b) have provided useful insight on massive star populations in starbursts, in particular because these objects cover a large metallicity range and, given the nature of WR stars, they represent the best probe of the upper end of the IMF. Recent reviews on WR galaxies are found in the IAU Symp. 193 (van der Hucht et al. 1999), Mas-Hesse (1999), and Schaefer (1999ab). Here we shall briefly summarise the main results from the large sample of Schaefer et al. (1999a) and Guseva et al. (2000).

In general a good agreement is found between the observations and the synthesis models of Schaefer & Vacca (1998), with a possible exception for some very low metallicity objects (Guseva et al. 2000, but also de Mello et al. 1998). This comparison indicates fairly short time scales of SF (bursts with $\Delta t \lesssim 2–4$ Myr) for the bulk of the objects at subsolar metallicity (mostly BCD galaxies). Again the IMF is compatible with a Salpeter slope and the existence of high mass stars is required. Similar conclusions are obtained by Mas-Hesse & Kunth (1999) and in earlier studies. The detection of WR stars of both WN and WC subtypes and the deduced WC/WN ratio provides strong constraints for stellar evolution models (see Schaefer et al. 1999a). This work was recently extended to a detailed analysis of five metal-rich starbursts which indicates a lower limit of $M_{\mathrm{up}} \gtrsim 30–40 M_\odot$ for the upper mass cut-off of the IMF in such environments (Schaerer et al. 2000).

New models synthesising the higher order Balmer and He I absorption lines were constructed by González Delgado et al. (1999ab; see references therein for earlier work). These lines are detected in a variety of objects (starbursts, Seyfert 2, post starbursts etc.) and provide useful information on massive (OB) star populations as well as later types (A). The first applications of these models to starbursts and H II regions are demonstrated in González Delgado et al. (1999b) and González Delgado & Pérez (2000). With no doubt this tool will be very useful to unravel massive star populations from integrated spectra.

4. Revealing starburst properties from nebular lines

Several types of diagnostics can be drawn from measurements of nebular lines:

- “Basic diagnostics”, i.e. quantities such as the total ionising photon flux, electron densities, temperatures, abundance ratios (requiring knowledge of $T_e$ and a correction for unobserved ionisation stages), which can be derived from first principles.

- “Advanced diagnostics”, such as the $R_{23}$ or $S_{23}$ metallicity indicators (e.g. Vilchez & Esteban 1996, Díaz & Pérez-Montero 2000) and stellar temperature indicators (softness parameter $\eta'$: cf. Vilchez et al. 1998; HeI/H$\beta$:...
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Kennicutt et al. 2000; [Ne iii]/Hβ: Oey et al. 2000), are based on empirical calibrations and/or photoionisation models.

- Other diagnostics require the use of photoionisation models.

In all cases the translation to the physical properties of interest here, i.e. the exciting stellar population, depends on the additional use of stellar atmosphere and stellar evolution models as well as on evolutionary synthesis models. Given the strong sensitivity of the derived parameters to these fundamental ingredients (stellar models) it is important to verify their reliability. In the following we shall briefly summarise the current status of such tests regarding the ionising fluxes from massive stars. The latest developments in stellar evolution models are reviewed in Maeder & Meynet (2000).

4.1. Ionising fluxes of O and WR stars: theory and observations

State-of-the-art atmosphere models for O stars include non-LTE effects, stellar winds and line blanketing (CoStar models: Schaerer & de Koter 1997; Pauldrach et al. 1998) which lead to important modifications of the ionising spectrum when compared e.g. to the popular plane parallel LTE models of Kurucz.

The implications of the CoStar fluxes on HII regions have been discussed by Stasińska & Schaerer (1997) and in various papers relying on these atmosphere models. Agreement is found for the predicted number of Lyman continuum photons, N_{Lyc}, from studies of nebulae with known stellar content (Oey & Kennicutt 1997). However, this does not represent very strong constraints since the observations provide a priori only a lower limit to N_{Lyc}, and for stars with T_{eff} \gtrsim 40 kK the predicted N_{Lyc} is little model dependent. Support for the predicted SED of the CoStar models in the Lyman continuum comes from comparisons of optical and IR observations to grids of photoionisation models (Stasińska & Schaerer 1997), detailed modeling of two LMC nebulae with known stellar content and a constrained ionisation parameter (Oey et al. 2000), and the agreement with the He I/H hardness (indicated by He I λ5876/Hβ) over a large range of T_{eff} shown in Figure 1. The work of Oey et al. (2000) indicates a possibly too hard spectrum in the 41-54 eV range. The first comparisons of the Pauldrach et al. (1998) models with HII region data shows a similar agreement with He I λ5876/Hβ (Kennicutt et al. 2000). Further detailed comparisons along the lines of the work of Oey et al. (2000) are necessary to provide accurate constraints on the atmosphere models. The reasonable success of the CoStar models indicates that such models can quite confidently be used in the interpretation of MSFR.

Due to the higher complexity (e.g. stratified ionisation, unknown hydrodynamics) of WR atmospheres their modeling is presently more uncertain than that of O stars. Although WR stars are less numerous than O stars, which usually dominate the ionising flux production, the former can in certain starburst phases contribute a non-negligible fraction of the ionising flux especially at high energies (e.g. Schmutz et al. 1992, Schaerer & Vacca 1998) and need thus to be investigated in a similar fashion. It is presently not fully clear how realistic the hardness predicted by the synthesis models is in these phases (e.g. Bresolin et al. 1999). Regarding this issue it must be recognised that this prediction depends not only on the atmosphere model used, but is also affected by the uncertainty
Figure 1. Observed and predicted H\textsc{e} I \(\lambda5876/\text{H}\beta\) ratio versus stellar effective temperature. Filled symbols: Observations of Galactic and LMC H\textsc{ii} regions from Kennicutt et al. (2000, cf. their Fig. 9) plotted versus temperature from using the Vacca et al. (1996) temperature scale. Open symbols: predictions from single star photoionisation models with Co\textit{Star} ionising fluxes for different ionisation parameters (Stasińska & Schaerer 1997). Models with their “standard” \(U\) are connected by the solid (dwarf stars) and dotted line (giants). The predictions are shown for solar and 1/5 solar metallicity (left and right panel).

in the link between the interior and atmosphere in these phases (cf. Schmutz et al. 1992), which is not discussed here.

The current status can be summarised as follows. First, evidence for hard spectra of hot WR stars (WNE, WC/WO) at low metallicity comes from the presence of nebular H\textsc{e} II \(\lambda4686\) emission in some WR nebulae and in many giant H\textsc{ii} regions harbouring WR stars (Garnett et al. 1991, Schaerer et al. 1999b) and the rather good quantitative agreement between predicted and observed nebular H\textsc{e} II (Schaerer 1996, de Mello et al. 1998). Indirectly this is also supported by the observations of O\textit{ IV} in IR spectra of two metal-poor galaxies (Schaerer & Stasińska 1999). Second, there is evidence against hard WR spectra at higher metallicities (\(\sim\) LMC – solar): few nebulae with H\textsc{e} II \(\lambda4686\) emission are known; line blanketed WR model atmospheres with softer spectra are in better agreement with the properties of WR nebulae (Esteban et al. 1993, Crowther et al. 1999); the observed EL ratios of H\textsc{ii} regions may be in conflict with photoionisation models incorporating the Schmutz et al. (1992) WR atmospheres and tracks from Maeder (1990; see Bresolin et al. 1999). The latter finding is, however, strongly model dependent and no such discrepancy is found in the models
of Stasińska et al. (2000) using up-to-date stellar tracks. Somewhat surprisingly also, unblanketed WR atmosphere models are quite successfully applied to PN with WR central stars (Peña et al. 1998).

It is thus well possible that the pure-He models of Schmutz et al. (1992) provide a reasonable description of the ionising fluxes of WR stars at low metallicity, while at LMC, solar and higher metallicities the spectra should be softer due to line blanketing. New developments of line blanketed WR atmospheres are in progress (see IAU Symp. 193, van der Hucht et al. 1999). This work should be of particular importance for the interpretation of young “metal-rich” starbursts.

4.2. Starbursts in the optical and IR

We shall now summarise recent work using combined evolutionary synthesis and photoionisation models to study the properties of starbursts from their optical and IR emission lines.

On one hand extensive model grids have been compared to samples of H
dot galaxy (e.g. García-Vargas et al. 1995, Stasińska & Leitherer 1996, Stasińska et al. 2000). In particular such studies have shown that at subsolar metallicities no variations of the IMF with O/H are necessary, contrary to earlier claims. Instead of studying global trends of EL ratios, the modeling of individual objects, for which sufficient observational constraints are available, is a complementary approach providing in particular more insight to fundamental physical processes responsible for the emission lines. We shall now briefly discuss few such recent studies.

The giant H
dot region NGC 7714 was modeled by Gracia-Vargas et al. (1997) based on optical spectra (including also stellar features) and on morphological information. A composite population consisting of a young burst and an older population including RSG was found. The main difficulties in reproducing the EL ratios concern [O i] \( \lambda 6300/H\beta \) and [O iii] \( \lambda 4363/5007 \), which are underpredicted by the model. NGC 2363 was recently modeled by Luridiana et al. (1999) based on optical spectra and H\alpha imaging. They find that the strategic line ratios are not reproduced by their model, if the metallicity derived from standard techniques is adopted. They suggest that temperature fluctuations may be present which would lead to an underestimate of O/H. Assuming a higher O/H leads to an agreement with most observed line ratios. Interestingly, as for NGC 7714, the temperature sensitive ratio [O iii] \( \lambda 4363/5007 \) is underpredicted in all of their models. Most clearly the problem of [O iii] \( \lambda 4363 \) is illustrated in the study of I Zw 18 by Stasińska & Schaerer (1999) using ground-based and HST UV–optical data. The failure to reproduce the electron temperature deduced from [O iii] \( \lambda 4363 \) indicates a missing energy source not included in the stellar photoionisation model. Although most observables can be reproduced by the combined starburst and photoionisation models — and the tool can thus be used to derive SB properties from the EL — one has to conclude that for accurate studies relying on nebular lines from H
dot regions (and presumably also more complex ob-

\footnote{Note: this is NOT a contradiction with their hypothesis of temperature fluctuations.}
jects) some additional physical process(es) (possibly shocks, conductive heating at X-ray interfaces etc.) must be taken into account.

Analysis of IR observations (mostly from SWS and LWS on ISO) of starbursts based on combined SB + photoionisation models are just beginning to appear in the literature. In this context it is useful to keep some intrinsic difficulties in mind are. Given the nature of objects and the large apertures involved, the integrated spectrum generally includes a large variety of regions. This fact, together with the complex geometries involved, render a priori the construction of photoionisation models difficult.

Simple models were constructed for case studies of Arp 299 and M82 by Satyapal et al. (1998) and Colbert et al. (1999) to interpret their LWS (40-200 µm) spectra. Colbert et al. (1999) find that the observed EL spectrum of M82 is compatible with an instantaneous burst at ages $\sim 3$–5 Myr, a Salpeter IMF, and a high upper mass cut-off. Surprisingly, inspection of models with similar ingredients (cf. Stasińska & Leitherer 1996), show that the shorter wavelength data (see Genzel et al. 1998) is clearly incompatible with the Colbert et al. model predicting too hard a spectrum. In view of the few line ratios originating from the H$^\text{II}$ gas and the large number of free parameters the photoionisation model is underconstrained. A larger wavelength coverage or other constraints are required.

Förster-Schreiber (1998) has described the geometry of clusters and gas clouds in M82 by a single “effective” ionisation parameter. This value has been adopted as typical for a sample of 27 starbursts in the SB + photoionisation models of Thornley et al. (2000). Instead of modeling a simple stellar population their models are based on an ensemble of H$^\text{II}$ regions following an observed luminosity function, which overall leads to a reduction, albeit small, of the hardness of the ionising spectrum. From the ISO/SWS [Ne $\text{III}$/[Ne $\text{II}$] line ratios they conclude that the observations are compatible with a high upper mass cut-off ($M_{\text{up}} \sim 50$–$100 \, M_\odot$). To reproduce the relatively low average [Ne $\text{III}$/[Ne $\text{II}$] ratio, short timescales of SF are required.

A different approach has been taken by Schaerer & Stasińska (1999), who modeled two well studied objects (NGC 5253, II Zw 40) with a fairly well known massive star population and existing UV-optical-IR observations. While their model successfully reproduces the stellar features and the observed ionisation structure of H, He, and O (as revealed from the optical and IR lines), the predicted IR fine structure line ratios of [Ne $\text{III}$/[Ne $\text{II}$], [Ar $\text{III}$/[Ar $\text{II}$], and [S $\text{IV}$/[S $\text{III}$] show too high an excitation. The origin of this discrepancy (atomic data? other?) is still unknown. In any case this attempt to describe two relatively “simple” objects illustrates the current limitations and shows that further progress is needed for a proper understanding and use of the IR fine structure lines as reliable diagnostics. Improvement is expected from multi-wavelength analysis of simpler objects (e.g. Galactic and LMC H$^\text{II}$ regions, PN) and other work. Such studies should be crucial to reliably extend the diagnostic tools to the IR to fully exploit the enormous observational capabilities provided by recent and upcoming facilities in probing the properties of massive star formation from the local Universe to high redshift.

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