THE MASSIVE STAR IMF AT HIGH METALLICITY

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Abstract The question of the variation of the upper IMF at high metallicity is briefly reviewed. I show recent results suggesting a revision in the definition of ‘high metallicity’ in extragalactic H II regions. I present preliminary results concerning constraints on the upper mass limit in metal-rich spiral galaxies derived from the detection of Wolf-Rayet stars in the spectra of their H II regions. The current evidence is in support of an IMF extending up to at least 60–70 $M_\odot$ at an oxygen abundance 1–1.5 times the solar value.

1. Questions asked

After roughly three decades since the pioneering work on the massive stellar content of extragalactic H II regions by Searle (1971) and Shields & Tinsley (1976), there is still space for discussions regarding the possible variation of the Initial Mass Function (IMF) properties at high metallicity. This question has been commonly investigated spectroscopically via the analysis of the nebular excitation produced by unresolved populations of stars, embedded in giant H II regions located within spiral galaxies. This method is prone to uncertainties, due to the model-dependent conclusions one can draw on the shape of the IMF. Despite the known presence of massive stars in the metal-rich Galactic center (see, for example, Figer in this volume) and the lack of evidence for variations of the IMF between the Milky Way and the comparatively metal-deficient Magellanic Clouds (Massey et al. 1995), we still need to investigate the possible dependence of the massive star IMF on additional factors, such as the star formation history, the stellar density, and the galactic Hubble type. Moreover, quantifying the chemical abundances in metal-rich star forming regions of spiral galaxies remains, perhaps somewhat surprisingly, an open issue.

In a recent review Schaerer (2003) covered several aspects of the massive star IMF, including the topic discussed in the current contribution.
I therefore concentrate on the most recent results and on some of the current work being done on the subject.

2. **A different IMF needed?**

The upper end of the mass function is loosely defined here as that tail composed by stars more massive than $20 M_\odot$, i.e. O and B stars with effective temperatures above 25,000 K. Although rare, these stars have an important feedback effect on galactic evolution, via the energy and momentum transferred to the interstellar medium by stellar winds, as well as its chemical enrichment, during their whole lifetime up to the supernova deflagration finale. The rarity and the short lifetimes (only a few Myr) of massive stars imply that we must account for statistical effects in the random sampling of the upper IMF, and that the stellar ensemble under consideration needs to be very young.

The notion that stars more massive than a certain threshold do not form at high metallicity (approximately solar and above) derives from early observational trends in samples of extragalactic H\textsc{ii} regions, combined with the accretion theory of Kahn (1974). The radial gradients in excitation, measured from the intensity of forbidden metal lines, and in the equivalent width of the nebular H\textbeta emission line in spiral galaxies led to the suggestion that the upper mass limit is lowered (Shields & Tinsley 1976) and that the slope of the IMF becomes steeper (Terlevich & Melnick 1981) at large metallicity. This idea has received support even recently from further optical and infrared spectroscopy of extragalactic H\textsc{ii} regions (among others: Goldader et al. 1997, Bresolin et al. 1999, Thornley et al. 2000). This interpretation relies on the observed softening of the radiation field at high metallicity, seen, for example, from the decreasing He\textsc{i} λ5876/H\beta line ratio in the optical (Bresolin et al. 1999, 2004) and from small fine-structure line ratios (e.g. [Ne\textsc{iii}]/Ne\textsc{ii}) in the mid-IR (Rigby & Rieke 2004; see Leitherer in this volume).

By contrast, the UV spectral properties of regions of active star formation do not support the idea of a varying IMF with metallicity. In particular, the strengths and P Cygni profiles of wind resonance lines, such as C\textsc{iv} λ1550 and Si\textsc{iv} λ1400, in supposedly metal-rich starbursts can be modeled with a ‘normal’ Salpeter-slope IMF extending up to $100 M_\odot$ (González Delgado et al. 2002). An additional direct probe for the presence of massive stars, the Wolf-Rayet (W-R) emission feature at 4660 Å, has been used to infer the extension of the IMF to large masses (> 30–40 $M_\odot$) even at the highest metallicities sampled (Schaerer et al. 2000, Bresolin & Kennicutt 2002, Pindao et al. 2002).
The dichotomy in the IMF properties derived from indirect (analysis of nebular lines) and direct (UV lines, W-R features) investigation methods seems now to be, at least in part, the result of the inadequacy of the stellar atmosphere models used in the past for the calculation of the ionizing flux output by hot and massive stars. As shown by González Delgado et al. (2002) and Rigby & Rieke (2004), the adoption of recent non-LTE stellar atmospheres, which include the effects of line-driven winds and line blocking from metals, into the evolutionary population synthesis models used for the interpretation of the spectra, leads to more standard conclusions regarding the upper IMF at high metallicity. In addition, complications arising from the effects of the nebular geometry and density structure of H\textsc{ii} regions conjure to make the determination of IMF parameters from nebular lines alone uncertain at best.

3. What is metal-rich?

The determination of chemical compositions is a topic where nebular lines do provide an essential insight into the physical and evolutionary status of star-forming galaxies. Most of our knowledge of radial abundance gradients in spiral galaxies derives, in fact, from the analysis of forbidden lines in H\textsc{ii} regions.

The presence of chemical abundance gradients in spiral galaxies is well-established, but recent extragalactic nebular abundance work is questioning the high end of the metallicity scale of previous investigations. Only recently the faint auroral lines used to determine direct electron temperatures of the nebular gas have become observable at high metallicity, where such lines become extremely faint, requiring large-aperture telescopes for their detection. In the case of M101, arguably the spiral galaxy with the best determination of an abundance gradient, Kennicutt et al. (2003) found a reduction of the central abundance by up to a factor of two with respect to indirect methods relying on strong emission lines (the R$_{23}$ indicator of Pagel et al. 1979). In the metal-rich spiral M51, the measurement of the auroral lines \[\text{[N II]}\lambda 5755\] and \[\text{[S III]}\lambda 6312\] from Keck LRIS spectra by Bresolin et al. (2004) in a significant number of H\textsc{ii} regions led to the determination of an extrapolated central abundance $\log(O/H) = -3.28$, a roughly solar value, and a factor up to 2-3 times lower than indicated by previous investigations. Figure 1 shows how different calibrations of the R$_{23}$ indicator exceed the abundance inferred from the electron temperatures, believed to represent the correct value.

This and similar results indicate that the term ‘high metallicity’ needs to be somewhat revisited when referring to extragalactic H\textsc{ii} regions.
Figure 1. Comparison between extragalactic H\textsubscript{II} region O/H abundances measured from electron temperatures (dots) and from the semi-empirical abundance indicator R\textsubscript{23}. The M51 data by Bresolin et al. (2004) are shown as solid circles. Two different calibrations are used for R\textsubscript{23}: Edmunds & Pagel 1984 (full line) and Pilyugin 2001 (dotted lines), the latter for two representative values of the excitation parameter.

Nebulae that in the past were considered to be of highly supersolar abundance, are very likely to be in the solar abundance regime, perhaps up to 50\% higher in the most extreme cases. The results mentioned earlier concerning the massive IMF in our own Galaxy and the lack of evidence for observable differences in the metallicity range bracketed by the Small Magellanic Cloud and the Milky Way might then imply that no variation in the upper mass limit is to be expected in the majority of putative metal-rich star forming galaxies. We might still have to find an H\textsubscript{II} region with 2–3 times the solar oxygen abundance.

4. Usefulness of W-R features

The detection and measurement of W-R features (e.g. the 4660 Å ‘bump’) in the spectra of extragalactic H\textsubscript{II} regions at high metallic-
ity, such as in the nucleus of the spiral galaxy M83 (Bresolin & Kennicutt 2002), offers a powerful method to constrain the upper mass cutoff of star-forming regions. This was elegantly shown by Pindao et al. (2002), who estimated the minimum mass of the most massive stars from model predictions of the equivalent width of the $\text{H}\beta$ emission line, an evolutionary chronometer for the ionizing stellar clusters, at the beginning of the W-R phase.

![Graph showing observational data for H II regions at high metallicity with W-R features in their spectra compared to the model predictions by Schaefer & Vacca (1998) for two different IMF slopes, and continuous and burst modes of star formation. By equating the observed $\text{H}\beta$ emission line equivalent width to its predicted maximum at the onset of the W-R phase, one obtains a lower limit for the upper mass limit of the IMF, $M_{\text{up}}$. The dark-grey symbols represent those H II regions for which we have reliably determined a solar oxygen abundance or above (in M51, M83 and NGC 1232) from measurements of their auroral lines. The light-grey symbols represent supposedly metal-rich objects from the compilation of Pindao et al. (2002, squares and triangles), and remaining H II regions from our VLT data.]

We have recently obtained VLT spectra with the purpose of analyzing the nebular properties, as well as the massive stellar (W-R) content,
of a sample of extragalactic H II regions contained in metal-rich galaxies (Schaerer, Bresolin, González Delgado & Stasińska, in preparation). Some preliminary results are displayed in Fig. 2, where I consider some of our new observational data about H II regions containing W-R features in NGC 1232, M83 and M51 (dark-grey circles), where the metallicity is confirmed from electron temperature measurements to be about solar, or slightly above that, together with the data compiled by Pindao et al. (2002, squares and triangles), and the other VLT targets for which our analysis is still incomplete (remaining light-grey symbols). Under the minimal assumption that in these objects the W-R phase just started (which corresponds to a maximum Hβ equivalent width), the evolutionary models of Schaerer & Vacca (1998) tell us that the IMF in these H II regions extends up to at least 60–70 $M_\odot$, for a Salpeter-slope IMF. If the abundance analysis of the remaining objects will confirm their high metallicity, which is currently just inferred from strong-line methods, we could push the minimum mass of the upper mass limit to even higher values, in agreement with the findings at lower metallicities.

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