OBSERVATIONAL CONSTRAINTS TO THE EVOLUTION OF MASSIVE STARS

N. PANAGIA
ESA/Space Telescope Science Institute
3700 San Martin Drive, Baltimore, MD 21218, USA
E-mail panagia@stsci.edu

Abstract. We consider some aspects of the evolution of massive stars which can only be elucidated by means of “indirect” observations, i.e. measurements of the effects of massive stars on their environments. We discuss in detail the early evolution of massive stars formed in high metallicity regions as inferred from studies of HII regions in external galaxies.

1. Introduction

Massive stars play a crucial role in the evolution of galaxies and the whole Universe, because they are the primary sources of radiative ionization and heating of the diffuse medium, they provide most of the nucleosynthesis products to boost the metal content of galaxies and the intergalactic medium, and they constitute a major supply of kinetic energy for galaxies, both through stellar winds during their quiescent phases and, eventually, in the form of fast ejecta from supernova explosions.

Therefore, it is fundamental to reach a proper understanding of the formation processes, the detailed properties and the evolution of massive stars. Despite the fact that their high luminosities make them “easy” targets for detailed observational studies, many aspects and properties of massive star evolution are far from being fully understood. This is because in any stellar generation, massive stars constitute a small fraction of the newly formed stars (say, less than 1% by number), they are “elusive” in that their lifetimes are very short (say, less than 10–20 million years), and often they are heavily obscured by the parent molecular clouds where they were formed, making even their identification rather cumbersome. As a consequence it is not easy to cover all evolutionary phases with direct observations of a statistically significant sample of objects.
One can overcome these difficulties and gain additional insights by considering phenomena that indirectly can provide hints and clues to the problem. In other words, besides studying individual massive stars, one can look at the effects that these stars have on their environments (e.g., HII regions, circumstellar nebulae, SNRs), and infer from there what the stars were doing in special phases of their evolution (e.g., formation, LBV and pre-SN phases, etc.) that would not be accessible in other ways.

Thus, one can use radio observations of supernovae, which probe the circumstellar material ejected by the progenitor stars several thousand years before explosion, to study the very last phases of their evolution. These phases represent a tiny fraction of a massive star lifetime, ~0.1%, and, therefore, they are extremely difficult to reveal and study with direct observations. Although this is an interesting aspect, we are not going to review it here, but rather we refer the reader to recent papers (Montes et al. 1998, Panagia et al. 1999, Weiler et al. 1999).

Here, we consider and discuss one particular aspect of the evolution of massive stars, namely their formation and early evolution in high metallicity environments. We will show that observations of HII regions in external galaxies show that the ionization of He is much lower than that of H when the O/H ratio in the gas is appreciably higher than solar. This implies that at high metallicities either very massive stars (M > 25 M⊙) do not form, or they never reach their expected ZAMS location.

2. Ionized Helium in the Milky Way

There is clear observational evidence in the H II regions of our Galaxy that the fractional abundance of ionized helium n(He↑+)/n(H↑+) is not a monotonic function of the galactocentric radius. Moving outwards from the Galactic Center, the ionized He abundance is found to increase in the inner Galaxy, then it attains a maximum near the solar circle, and finally drops in the outer Galaxy (e.g., Mezger & Wink 1983 and references therein). The negative gradient in the outer galaxy reflects a genuine decrease in the He abundance in the outward direction (e.g., Panagia 1980; Güsten & Mezger 1982). The positive gradient in the inner Galaxy instead is an effect of the radial metallicity gradient which produces a systematic variation of the spectrum of the ionizing radiation (Panagia 1980).

The fractional ionization of helium is extremely sensitive to the most energetic part of the radiation field powering an H II complex. Hence, it can provide valuable information on the presence and the abundance of the most massive (m ≥ 20 M⊙) stars, which are responsible for most of the radiation with energy in excess of 24.6 eV. Therefore, it is a powerful tool to study how the details of the star formation process vary in differ-
ent physical environments. There are several mechanisms through which a higher metallicity lowers the He ionization in an H II region:

- The relative number of He-ionizing photons in the stellar spectrum is reduced because of both a stronger line blanketing in the 200–500 Å wavelength range, and a higher continuum opacity.
- The stellar radius becomes larger and the effective temperature decreases for a star of given mass, because of the increased continuum opacity in the sub-atmospheric layers of the star.
- The upper cut-off of the Initial Mass Function (IMF, $m_U$, may be shifted to lower masses (e.g., Kahn 1974; Shields & Tinsley 1976).
- A higher metallicity may induce a steeper IMF (i.e. a larger value of the slope $\alpha$ of the IMF $N(m) \propto m^{-\alpha}$) at least for $m > 10 \, M_\odot$, where the bulk of the ionizing radiation is produced (e.g., Terlevich & Melnick 1983).

In the first two cases, metallicity acts “directly” on the radiation field of the ionizing star cluster, by modifying the stellar spectra without affecting the star formation processes. In the third and fourth case instead, metallicity acts “indirectly” and the changes in the radiation field result from changes in the properties of the IMF.

Panagia (1980) demonstrated that the combined effects of at least the first three processes are needed to explain the He ionization in the Milky Way. Moreover, these processes appear to account for the observed gradient of the effective temperature of the ionizing radiation inferred from the fitting of theoretical models to observations of low-metallicity objects (Talent 1980; Campbell 1988).

3. Ionized Helium in External Galaxies

Considering external galaxies, several authors (e.g., Pagel 1986, Viallefond 1988, Robledo-Rella & Firmani 1991) have suggested that a systematic change of the IMF with metallicity is required by observations. Others (e.g., Fierro, Torres - Peimbert & Peimbert 1986, McGaugh 1991) have come to the opposite conclusion, and the controversy is still open. A thorough assessment of this subject is now possible and necessary.

We have considered a large sample of extragalactic H II regions which provides an extensive coverage of a very wide metallicity range (almost a factor of 100), and includes galaxies with a variety of morphological types and luminosities. Such a sample is in many respects much more homogeneous than any sample of galactic H II regions. All the H II regions observed are large (diameter D > 50 pc), tenuous ($n_e < 500 \, \text{cm}^{-3}$ as derived from the $[S\, II] \, \lambda\lambda6717,6731$ ratio) and must be ionized by large OB associations.

Here, we limit our analysis to data published as of February 1992. (A more complete investigation, including the discussion of data published as
of December 1999, is in progress and will be completed soon; Lenzuni and Panagia 2000, in preparation). Thus, our sample currently includes 287 H II regions in 46 spiral and irregular galaxies with positive detections of the [O II] lines at 3726 and 3729 Å (usually unresolved), of the [O III] lines at 4959 and 5007 Å, and of at least one of the He I lines. Additional observations were also collected for 87 “Blue Compact Galaxies” (BCG’s). None of these objects is resolved into individual H II regions, the observations being relative to the entire galaxy or, possibly, to its central, brightest parts. These galaxies appear to be undergoing a stage characterized by a collective mode of star-formation. Their spectra are heavily dominated by H II region-like emission, hence they can be treated for our purposes as giant, isolated, extragalactic H II regions.

4. Analysis and Discussion

Ionized helium abundances are shown in Figure 1 as a function of oxygen abundances, for all of the H II regions in spiral and irregular galaxies and the Blue Compact Galaxies of our sample. The long baseline in metallicity offers a unique opportunity to constrain both the abundance of primordial helium \( Y_P \) and to the \( \Delta Y/\Delta Z \) gradient, thus fully determining the “helium enrichment curve” (HEC) which relates the total abundance of helium to the abundance of oxygen. Considering that evolutionary effects always decrease the \( \text{He}^+/H^+ \) ratio because the aging of a stellar cluster results in a softening of the ionizing radiation field, and that young clusters are observationally favoured because they are intrinsically brighter than older clusters, the HEC can be derived by determining the upper envelope of the distribution shown in Figure 1. Among the class of curves \( Y = Y_0 + \Delta Y/\Delta Z \times Z \) the best fit to the upper envelope of the observations is obtained for \( Y_0 = 0.243 \) and \( (\Delta Y/\Delta Z)_\odot = 3.2 \) (see dashed curve in Fig. 1). This relation is consistent with the observational results of Pagel et al. (1992) as well as with Maeder’s (1992) theoretical models.

An inspection to Figure 1 reveals that the observed \( \text{He}^+/H^+ \) ratio appears to be almost constant up to solar O abundance \( \log(O/H)_\odot +12 \simeq 8.8 \) and then it declines rather quickly for higher metallicities. This is a clear sign that He is progressively less ionized as the O abundance increases, and implies that the mean radiation temperature of the ionizing stars becomes lower than about 38,000 K around \( \log(O/H) \simeq 8.5 \).

We find that mechanisms through which metallicity acts “directly” on the radiation field of the ionizing star cluster are not enough to explain the observed gradient of the He ionization fraction with O abundance. Most of the effect appears instead to be due to “indirect” mechanisms, i.e. a marked deficiency of hot stars with increasing metal abundances. There are at least
three possible scenarios to explain this fact:

1. The IMF slope becomes steeper for higher metallicities.
2. The IMF upper cutoff moves to lower masses for higher metallicities.
3. The most massive stars become progressively unable to provide ionizing radiation, either because at high metallicities the remnant of their pre-MS cocoons remains optically thick over most of a star’s lifetime, or because pulsational instabilities prevent the most massive stars from reaching their expected ZAMS surface conditions.

Our model calculations show that varying only the slope of the IMF, i.e. point (1), does not give a satisfactory fit to the data because the resulting ionization decline would be too shallow. On the other hand, point (2), i.e. a systematic variation of the IMF upper mass cut-off with metal abundance ($m_U \propto Z^{-\beta}$, $\beta > 0$) can reproduce the observed trend of the He ionization, with $m_U/M_\odot = 48 M_\odot$ and $\beta = 0.60$. Point (3) could also account for the observations provided that the invoked effects are indeed capable to
produce the sharp decline of He ionization as observed.

From the observational point of view there are no direct studies to conclusively discriminate between points (2) and (3). Observations of massive stars near the Galactic Center, such as the Pistol star, the Sickle and the Quintuplet clusters (e.g., Figer et al. 1999 and references therein) seem to favor the third possibility, because they are so bright ($\log(L/L_\odot) > 6$) that they must be quite massive. On the other hand, one may argue that those clusters are so close to the Galactic Center that tidal forces may drastically affect the dynamical processes that lead to the formation of stars and, therefore, they may not be representative of normal situations. The ideal investigation to clarify this issue should include nebular and stellar spectroscopy of a large sample of HII regions in galaxies which display marked effects of incomplete He ionization, such as M51 or M83. Another discriminant between hypotheses (2) and (3) is that if a lowering of the IMF upper cutoff is the explanation (i.e. point (2)), then the frequency of Wolf-Rayet stars relative to early type stars is expected to be abnormally low in the high-Z regions because in this case the reduced ionization is entirely due to the lack of truly massive stars that are expected to end up as WR stars in their final stages of evolution.

References

1. Campbell A., 1988, Ap. J. 335, 644
2. Fierro J., Torres-Peimbert S., Peimbert M., 1986, P.A.S.P. 98, 1032
3. Figer, D., McLean, I.S., Morris, M., 1999, Ap. J. 514, 202
4. Güsten R., Mezger P., 1982. Vistas in Astronomy 26, 159
5. Kahn F.D., 1974, Astr. Ap. 37, 149
6. Maeder A., 1992, Astr. Ap. 264, 105
7. McGaugh S.S., 1991, Ap. J. 380, 140
8. Mezger P.G., Wink J.E., 1983, in Primordial Helium, eds. P.A. Shaver, D. Kunth and K. Kjär (ESO, Garching, Germany)
9. Montes, M.J., Van Dyk, S.D., Weiler, K.W., Sramek, R.A., Panagia, N., 1998, Ap. J. 506, 874
10. Pagel B.E.J., 1986, in Highlights of Astronomy Vol. 7, ed. J.P. Swings (Reidel, Dordrecht, The Netherlands)
11. Pagel B.E.J., Simonson E.A., Terlevich R.J., Edmunds M.G., 1992, M.N.R.A.S. 255, 325
12. Panagia N., 1980, in Radio Recombination Lines, ed. P. A. Shaver (Reidel, Dordrecht, The Netherlands)
13. Panagia, N., et al., 1999, Mem S.A.It., in press
14. Robledo-Rella V., Firmani C., 1990, Rev. Mexicana Astron. Astrof. 21, 236
15. Shields G.A., Tinsley B., 1976, Ap. J. 203, 66
16. Terlevich R.J., Melnick J., 1983, M.N.R.A.S. 195, 839
17. Viallefond F., 1988, in Galactic and Extra-Galactic Star Formation, eds. R. Pudritz and M. Fich (Reidel, Dordrecht, The Netherlands)
18. Weiler, K.W., et al., 1999, in “The Largest Explosions since the Big Bang: Supernovae and Gamma Ray Bursts”, eds. M. Livio, K. Sahu & N. Panagia, (CUP, Cambridge, England), in press