

On the equivalent effective temperatures of massive young star clusters: The case of NGC 595

Enrique Pérez-Montero¹, José M. Vílchez¹, Mónica Relaño², and Ana Monreal-Ibero¹

¹ Instituto de Astrofísica de Andalucía - CSIC. Apdo. de correos 3004, Granada, Spain

² Universidad de Granada, Campus Fuentenueva, Granada, Spain

Abstract

The softness parameter is based on the relative intensity of several optical emission lines emitted by the gas ionized by young massive star clusters and can be used to derive the equivalent effective temperature (T_*) in those objects whose stellar population cannot be resolved. This method has several uncertainties due to the disagreement between different synthesis model atmospheres but it is robust to study the relative variations between objects. Following the 2D photoionization models of the giant HII region NGC 595 (Pérez-Montero et al. 2011) we show that the determination of T_* with the η parameter is also robust in different regions of a same object with large variations in the geometry of the gas and in the dust-to-gas ratio.

1 Introduction

The study of the properties of young massive star clusters in our Local Group can be done by means of the census of the stars that belong to the corresponding object and the analysis of their properties using a colour-magnitude diagram. In the case of those objects whose stellar population cannot be resolved with the facilities that are nowadays available, it is necessary to appeal to other techniques. A possible approach is to study the massive stars by inspecting their effects on the surrounding interstellar medium (ISM), including the supply of mechanical energy from stellar winds and supernovae explosions, the ejection of new metals produced in the interiors of the stars, or the excitation and ionization of the atoms in the ISM by the energetic photons emitted by the stars. These factors make the optical spectrum of an HII region to be frequently characterized by the presence of bright prominent recombination lines emitted by hydrogen and helium and of collisional lines emitted by the metals. Although the shape of the stellar continuum and some stellar features are sometimes detectable (*e.g.* the Wolf-Rayet features), the most important source of information about the properties of the ionizing stellar clusters can only be the relative intensities of these lines.

These intensities are mainly dominated by the so-called functional parameters, including the metallicity (Z), the ionization parameter (U , *i.e.* the ratio between ionizing photons and the density of particles), and the equivalent effective temperature (T_*). This last is the unique parameter that only depends on the spectral energy distribution (SED) of the ionizing star or cluster.

2 The *softness* parameter

This parameter, denoted by the greek letter η , was introduced by Vílchez & Pagel (1988) to derive T_* using only the information from emission-line intensities in the optical spectrum. It is defined as:

$$\eta = \frac{O^+/O^{2+}}{S^+/S^{2+}} = \frac{[OII]3727\text{\AA}/[OIII]4959, 5007\text{\AA}}{[SII]6717, 6731\text{\AA}/[SIII]9069, 9532} + o(Z) \quad (1)$$

depending mainly on the ionic abundances of oxygen and sulphur ions. This ratio is basically a function of the ratio between the number of ionizing photons of O^+ (I.P. = 35.1 eV) and S^+ (I.P. = 23.3 eV) and has also a certain dependence on the overall metallicity [$o(Z)$] when it is derived directly from the emission-line intensities.

In the ideal case of a blackbody it only has a linear relation with the slope of the SED, but for young massive star atmospheres it noticeably changes for different model atmospheres. In upper panels of Fig. 1 we show the SEDs of WM-Basic (Pauldrach et al., 2001 with an expanding spherical geometry) at left and Tlusty (Hubeny & Lanz, 1995, with a plane-parallel geometry) at right for a same value of T_* (40000 K) and different values of the metallicity. The slope and the shape of the SEDs can be very different in the energetic range covered by the optical η parameter (Simón-Díaz & Stasińska, 2008). An alternative to the optical η parameter was proposed for the mid-infrared spectral range with emission lines of [NeII] (12.8 μm), [NeIII] (15.6 μm), [SIII] (18.7 μm), and [SIV] (10.5 μm) (Martín-Hernández et al., 2002; Morisset et al. 2004), but this involves an even more energetic range between the ionization potentials of S^{2+} (I.P. = 34.8 eV) and Ne (I.P. = 40.5 eV), where discrepancies between the different synthesis model atmospheres are larger (see Pérez-Montero & Vílchez, 2009, for a more detailed discussion).

In the lower panels of Fig. 1 we show the relation between the optical emission-line ratios of oxygen ([OII]/[OIII]) and sulphur ([SII]/[SIII]) for a sample of objects with emission-line like spectra compiled by Pérez-Montero & Vílchez (2009). The solid lines are quadratical fits to different sets of Cloudy (Ferland et al., 1998) photoionization models with different values of T_* (from 35 kK to 50 kK). At left, these models are calculated using WM-Basic stellar atmospheres and, at right, Tlusty (see Pérez-Montero & Vílchez to see a deeper description of these models). As can be seen, there are substantial differences between the two studied synthesis model atmospheres. These differences prevent an accurate determination of the absolute value of T_* in HII regions but, apparently, allows a good relative characterization for different families of objects. In both panels, Circumnuclear Star Forming Regions (CNSFRs) and HII galaxies have the higher temperatures and, in contrast, smaller regions in our Galaxy and the Magellanic Clouds have lower temperatures.

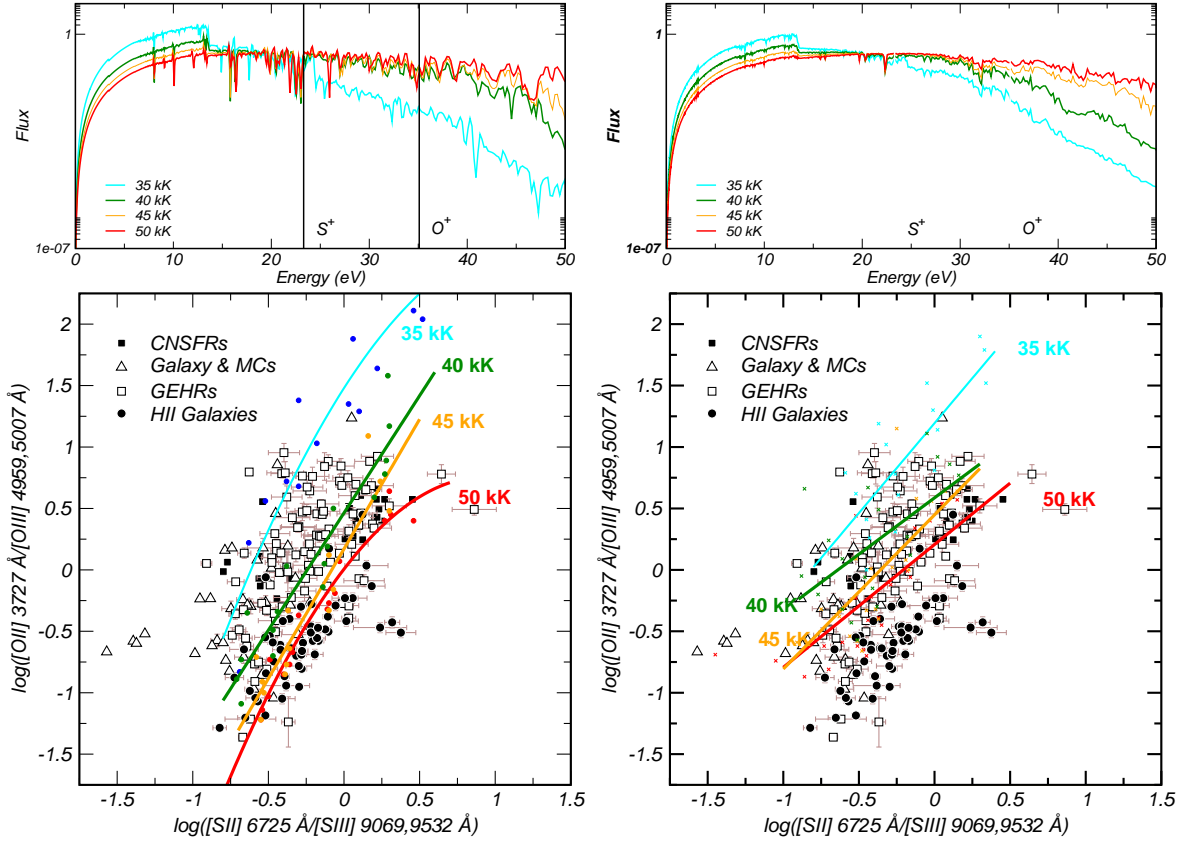


Figure 1: Upper panels: SEDs of synthesis model atmospheres from WM-Basic (left) and Tlusty (right) for different values of the metallicity and $T_* = 40$ kK. The vertical solid lines represent the ionization potentials of S⁺ and O⁺. In the lower panels we show the relation between the ratios of optical emission line-intensities [OII]/[OIII] and [SII]/[SIII] for different objects. The solid lines show the quadratical fits to sets of photoionization models with stars of different equivalent effective temperatures from WM-Basic (left) and Tlusty (right).

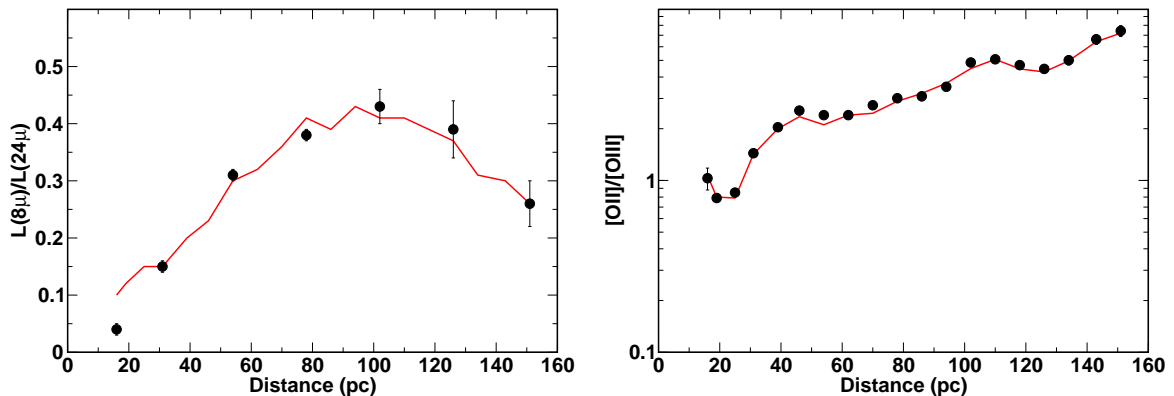


Figure 2: Variations of the 8 to 24 μm ratio (at left) and optical $[OII]/[OIII]$ at right for different elliptical apertures around the central ionizing cluster in the giant HII region NGC 595. Black points represent the observed properties and the red solid line the results from tailored photoionization models for each of these apertures (from Pérez-Montero et al., 2011)

3 The case of NGC 595

One of the possible caveats when using the η parameter to find out T_* in massive star clusters is due to that the information comes from the ionized gas. This implies that possible variations in the properties of the gas other than the functional parameters, such as gas geometry or density, or dust structure could also affect to the η parameter.

We used as a test to check to what extent these variations can affect to the determination of T_* the Cloudy photoionization models of the 2D structure of the giant HII region NGC 595 (Pérez-Montero et al., 2011). The observational inputs for these models come from integral field spectroscopy taken with the PMAS instrument at the CAHA 3.5m telescope in the optical range between 3700 Å - 6800 Å (Relaño et al., 2010) and photometric information from Spitzer space observatory at 8 and 24 μm filters. In these models it was assumed a single ionizing source for all the HII region according to the properties of the CMD diagram derived by Malumuth et al. (1996). These models reproduce the variations in the optical and mid-IR properties for different elliptical aperture regions with similar observational properties by assuming different matter-bounded geometries combined with different dust-to-gas ratios, in good agreement to the dust-to-gas ratio derived in the integrated region (Pérez-Montero et al., 2011). In Fig. 2, we show the comparison between the models and the observations in each elliptical aperture.

In Fig. 3 we show the relation between the two optical emission-line ratios $[OII]/[OIII]$ and $[SII]/[SIII]$ involved in the η parameter with the fits to the photoionization models with *TLUSTY* atmospheres shown in lower right panel of Fig. 1. The black circles represent the values derived from the tailored models for each region in NGC 595. As can be seen, with the exception of some models, the most part of the elliptical apertures lie in regions consistent with a single value of T_* across the nebula, independently on the inner variations in the geometry of the gas and in the dust-to-gas ratio. The value of T_* (between 35 kK and 40 kK) is consistent to the value associated with the properties of the cluster derived by

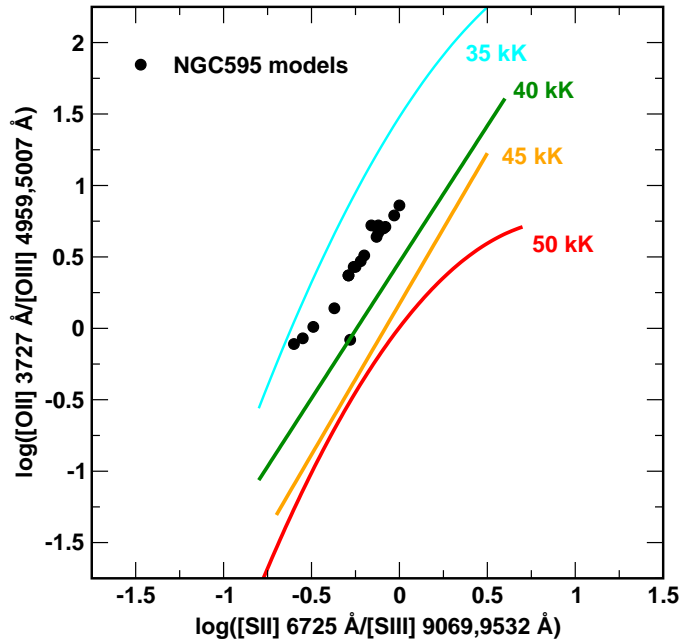


Figure 3: Relation between the optical emission-line ratios $[\text{OII}]/[\text{OIII}]$ and $[\text{SII}]/[\text{SIII}]$. Solid lines represent the same fits to grids of photoionization models of different T_* for Tlusty atmospheres represented in Fig. 1. Black circles represent the models for NGC 595 derived by Pérez-Montero et al. (2011)

Malumuth using a CMD diagram, which is around 40 kK. It must be noted, however, that neither the slope of the grid of models for NGC 595 nor the slopes of the grids of models for different T_* are equal to 1, which is the value of the slope for the lines with different η across the diagram, so this implies that this parameter must not be used as one-dimensional. In contrast, its analysis must be undertaken using a 2D approach as in this case. For instance, in the models of NGC 595, there is a variation in η in a factor 2 which is not contradictory with an homogeneous value of T_* in the models.

4 Conclusions

The determination of properties of a massive young stellar cluster can be obtained by using information from the emission line spectrum from the ionized gas in those cases where the stellar population of the cluster cannot be resolved. The η parameter as analyzed in 2 dimensions is a robust method to derive the equivalent effective temperature of a cluster, even in those cases where there are variations in the geometry of the gas or in the dust-to-gas ratio. The most important caveat appears as a consequence of the disagreements in the involved energetic ranges between different synthesis model atmospheres, but it is possible to use this to study the relative variations of T_* in homogeneous samples of objects. This is the case of the variation of T_* across spiral disks found by Pérez-Montero & Vílchez (2009), which points to a hardening of the ionizing radiation above all in spiral galaxies of low dynamical mass and luminosity with late morphological type.

Acknowledgments

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References

- [1] Ferland, G.J., Korista, K.T., Verner, D.A., Ferguson, J.W., Kingdom, J.B., & Verner, E.M., 1998, *PASP*, 110, 761
- [2] Hubeny, I., & Lanz, T., 1995, *ApJ*, 439, 875
- [3] Martín-Hernández, N. L.; Vermeij, R., Tielens, A.G.G.M., van der Hulst, J.M., & Peeters, E., 2002, *A&A*, 389, 286
- [4] Malumuth, E.M., Waller, W.H., & Parker, J.W., 1996, *AJ*, 111, 1128
- [5] Morisset, C., Schaerer, D., Bouret, J.-C., & Martins, F., 2004, *A&A*, 415, 577
- [6] Pauldrach, A.W.A., Hoffmann, T.L., & Lennon, M., 2001, *A&A*, 425, 849
- [7] Pérez-Montero, E., Relaño, M., Vílchez, J.M., Monreal-Ibero, A., 2011, *MNRAS*, 412, 675
- [8] Pérez-Montero, E. & Vílchez, J.M., 2009, *MNRAS*, 400, 1721
- [9] Relaño, M., Monreal-Ibero, Vílchez, J.M., & Kennicutt, R.C., 2010, *MNRAS*, 402, 1635
- [10] Simón-Díaz, S., & Stasińska, G., 2008, *MNRAS*, 389, 1009
- [11] Vílchez, J.M., Pagel, B.E.J., 1988, *MNRAS*, 231, 257