On the hardening of the ionizing radiation in HII regions across galactic discs through softness parameters

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\begin{abstract}

We carry out a study of the hardness of the radiation of ionizing clusters in HII regions. Firstly, we explore the applicability of the softness parameter \( \eta \), originally defined in the optical for pairs of consecutive ionization stages of the same species. With the advent of the infrared space observatories, this definition has been extended to the mid-infrared. We show that the softness parameters, as determined both in the optical and the mid-infrared wavelengths, are sensitive to the effective temperature using a sample of data in both spectral regimes. This is confirmed by comparing the data with a grid of photoionization models, although no complete agreement has been found even for different stellar model atmospheres. Finally, we show that both softness parameters are consistent in the search for radial variations of the hardness of the ionizing radiation of HII regions in the discs of spiral galaxies. We find a range of trends, from galaxies showing pronounced gradients to those showing very flat ones. Although the detectability and slope of these gradients can be altered by the size and luminosity of the studied HII regions, it looks that their existence is related to the mass and type of the galaxies and, hence, to the properties of the entire disc.

\textbf{Key words:} ISM: HII regions \& galaxies : ISM \& galaxies : spiral

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\section{1 INTRODUCTION}

The radiation field emitted by massive stars ionizes the interstellar medium producing the HII regions. These regions are found preferentially in gas-rich galaxy discs and star-forming dwarf galaxies and remain a powerful tool to investigate many relevant properties of the interstellar medium (ISM; metallicity, density, temperature) and of the massive stellar populations of galaxies (star formation rate, spectral energy distributions, IMF, among others).

Since the pioneering works of Searle (1971) the observation of giant HII regions in the discs of nearby spirals has revealed the existence of gradients of the excitation of the ionized gas, as measured by the ratio of [OIII]/H\beta lines. These excitation gradients were originally associated to the existence of chemical abundance gradients across the galaxies (Smith, 1975), nowadays a general property of spiral discs (e.g. Pilyugin et al., 2004). In addition to the abundance gradient, it was originally found that a gradient in the hardness of the ionizing spectral energy distribution (SED) was necessary in order to produce a detailed modeling of the spectra of (inner) HII regions in some spiral galaxies (Shields \& Searle, 1978). Indeed, the spectral sequence of (near zero-age/main sequence) giant HII regions has been shown to be driven by three main \textit{functional} parameters: metallicity, \textit{effective} ionizing temperature and ionization parameter (e.g. McCall et al., 1985), allowing for a certain evolution of the ionizing stars and their nebulae (e.g. Stasińska \& Schaerer, 1997).

In order to put these earlier suggestions on a firmer observational basis, the degeneracy between the spectral parameters excitation and metallicity must be broken, since the spectral observables of effective temperature, ionization parameter and metallicity are usually self-correlated. In this vein, Vílchez \& Pagel (1988) defined a methodology to evaluate the effective temperature of the ionizing stars in HII regions independently (to first order) of the value of the ionization parameter; they used Osterbrock’s equation for the abundance equilibrium of two consecutive ionization stages of two different species to produce a SED “radiation softness” parameter, thus removing the dependence on the ionization parameter:

\begin{equation}
\frac{n(X^{i+1})}{n(X^i)} = \frac{u \langle \sigma^i \rangle}{\beta(X^i)} \frac{Q(X^i)}{Q(H)}
\end{equation}

where \( n(X^i) \) is the number density of the \( i \)-times ionized atoms of the element \( X \), \( u \) is the ionization parameter, \( c \) is the speed of the light, \( \langle \sigma^i \rangle \) is the mean value of the photoionization cross-section of \( X^i \), \( \beta(X^i) \) is the total recombination coefficient, \( Q(X^i) \) is the number of ionizing photons of the ion \( X^i \) and \( Q(H) \) the number of ionizing photons of hydrogen. Since the quotient of ionizing photons is sensitive to the shape of the ionizing SED and, hence, to the harden-
ing of the radiation, this quantity can be used to derive the effective temperature. The dependence on the ionization parameter can be removed (to first order) by taking the ratio of two different quotients. This method can be used for any pair of chosen consecutive ionization stages. Therefore, using the available emission lines in the optical range of the HII region spectrum, an optical “radiation softness” parameter was defined as:

$$\eta = \frac{O^{+}/O^{2+}}{S^{+}/S^{2+}},$$

which does not show a strong dependence on the electron temperature and it is proportional to the corresponding ratio based on the emission lines,

$$\eta' = \frac{I([OII]\lambda3727)/I([OIII]\lambda4959, 5007)}{I([SII]\lambda6717, 6731)/I([SIII]\lambda9069, 9532)}$$

where all the wavelengths are in Å. This parameter results inversely related to the effective temperature, given the difference in the ionization potentials involved (O$^{+}$ IP 35.1 eV; S$^{+}$ IP 23.3 eV). Then, combining $\eta$ with one of theionic quotients we can solve also for $u$.

More recently, Martín-Hernández et al. (2002) and Morisset et al. (2004), among others, have explored the use of similar softness parameters defined using the intensities of emission lines available in the mid-infrared (mIR), in particular, based on Ar, Ne and S fine structure emission lines. Nevertheless, until recently it has not been possible to carry out an empirical test of these mIR “softness” parameters; presently this test is possible given the amount of data now available from space-based observations with Spitzer Space Telescope, in addition to previous data from the Infrared Space Observatory.

Spiral galaxies can offer the best laboratory to check, in a consistent way, the validity of these mIR softness parameters, since the HII regions in these discs have been observed under similar conditions and analyzed consistently. At present, there is a useful source of data available of mIR emission lines of [Ne$^{ii}$], [Ne$^{iii}$], [S$^{ii}$] and [S$^{iii}$] in HII regions of spiral discs (see Table 1). With this information, a “softness” parameter in the mIR can be defined as follows:

$$\eta'(mIR) = \frac{I([Ne^{ii}]\lambda12.8\mu m)/I([Ne^{iii}]\lambda15.6\mu m)}{I([S^{ii}]\lambda18.7\mu m)/I([S^{iii}]\lambda10.5\mu m)}$$

To keep the negative correlation with the effective temperature—as in the definition of the optical parameter—we used the line of Ne$^{+}$ (IP 41.0 eV) in the numerator over the line of S$^{2+}$ (IP 34.8 eV). The study of the behaviour of this quotient using photoionization models (Morisset et al., 2004; Simón-Díaz & Stasińska, 2008) indicates a very slight dependence on the stellar atmosphere used in the models; and recent studies using a larger empirical database (cf. Groves et al., 2008) point to a clear offset of the AGNs when viewed within the same framework.

Although recent evidences point towards possible variations in the ionizing SEDs of HII regions across spiral discs, yet it remains unknown whether this behaviour appears an “universal” feature of spiral galaxies. In particular, we do not know to which extent real gradients of the ionizing SEDs do exist in spiral galaxies; whether these (possible) gradients of the ionizing SEDs could be parameterized in terms of the physical/chemical properties of spiral galaxies remains to be studied. With this aims, in this work we study empirically the applicability of both, optical and mIR softness parameters and make an exam of our results in the light of the predictions of a set of photoionization models. Then, using recent high quality data of HII regions for a sample of spiral galaxies, we make a consistent study of the behaviour of the (gradients of) hardening of the ionizing radiation across their discs, as traced by the emission lines of their bright HII regions. Finally, we discuss the results obtained and present our conclusions.

### 2 EMPIRICAL ”SOFTNESS” PARAMETERS AND PHOTOIONIZATION MODELS

We have made a selection from the recent literature of all high quality emission line fluxes necessary to calculate both, the optical and mIR softness parameters. In the case of the optical, we took the reddening-corrected spectroscopic data used in Pérez-Montero et al. (2006), with the addition of the HII galaxies studied in Hägeler et al. (2008), a sample of metal-rich HII regions in spiral discs (Bresolin et al., 2006) and the Circumnuclear Star Forming Regions (CNSFRs) studied in Díaz et al. (2007).

In the case of the mIR, we have compiled spectroscopic data from different sources corresponding to ISO and Spitzer observations. Table 1 lists the compiled objects along with their references and the source of observations.

We make use of the photoionization code CLOUDY 08.00 (Ferland et al., 1998), taking as ionizing source the SED of metal line-blanketed, NLTE, plane-parallel, hydrostatic model atmospheres of O stars calculated with the code TLUSTY (Hubeny & Lanz, 1995). We assumed spherical geometry, a constant density of 100 particles per cm$^3$ and a standard fraction of dust grains in the interstellar medium. We assumed as well that the gas metallicity is the same for the ionizing source, covering the values $Z_{\odot}$/$30, Z_{\odot}$/$10, Z_{\odot}$/$5, Z_{\odot}$/$2$ and $Z_{\odot}$, taking as the solar metallicity the oxygen abundance measured by Asplund et al. (2005); $12+\log(O/H) = 8.66$. The rest of ionic abundances have been set to their solar proportions. A certain amount of depletion was taken into account for the elements C, O, Mg, Si and Fe, considered for the formation of dust grains in the code. Regarding other functional parameters we considered different values.

#### Table 1. Bibliographic references for the mid-IR emission line fluxes of the compiled sample from Spitzer ($^a$) and ISO ($^b$).

| Reference | Type or host | Pointings |
|-----------|--------------|-----------|
| Beirão et al., 2008$^a$ | M82 | 6 |
| Dale et al., 2009$^a$ | GEHRs | 149 |
| Engelbracht et al., 2008$^a$ | BCDs | 41 |
| Giveon et al., 2002$^b$ | MW | 101 |
| Gordon et al., 2008$^a$ | M101 | 6 |
| Lebouteiller et al., 2008$^a$ | MW & MCs | 31 |
| Rubin et al., 2007$^a$ | M33 | 25 |
| Rubin et al., 2008$^a$ | M83 | 23 |
| Verma et al., 2003$^b$ | BCDs | 12 |
| Vermet et al., 2002$^b$ | MCs | 14 |
| Wu et al., 2007$^a$ | BCDs | 11 |
| **Total** | | 422 |
of the ionization parameter ($\log U = -3.5$, -3.0, -2.5 and -2.0) and of the stellar effective temperature ($T_* = 35000$ K, 40000 K, 45000 K and 50000 K). This gives a total of 80 photoionization models intended to cover the range of conditions of different ionized gas nebulae.

3 RESULTS AND DISCUSSION

In Figure 1 we show the relations between the ratios of emission lines used to define both the optical and the mIR softness parameters. Both $\eta'$ are obtained directly by the lines of slope 1 with the same difference between the $y$ and the $x$ axis. The models are represented by crosses and the best linear fit to each set with the same effective temperature are represented as solid lines of different colours.

In the left panel, we show the plot of the optical softness parameter. The models fit reasonably well the data, with the probable exception of HII galaxies, which present abnormally high effective temperatures as compared with the scale of the models; these values can be even higher than the stellar atmospheres with effective temperature of 50 kK. This feature has been previously related to a (claimed) additional source of heating in these objects (e.g. Stasińska & Schaerer, 1999). At same time, we can observe that higher effective temperatures correspond to lower values of the $\eta'$ parameter. On the other hand, as was already found by Morisset (2004), lower metallicities lead to lower values of $\eta'$, but this effect is sensibly lower in the considered range of metallicity than those caused by differences in stellar effective temperature. Anyway it precludes to provide a precise calibration of the effective temperature as a function of this parameter.

In the right panel, we show the equivalent plot for the emission line ratios of the mid IR softness parameter. In this case, there is not a general agreement between the compiled data and the predictions of the models for all the stellar temperatures; in such a way that a large fraction of the objects (mostly GEHRs) appears to be located in a region of the diagram corresponding to effective temperatures lower than 35 kK This mismatch, already found by Morisset et al. (2004), does not look to be caused by the use of specific sets of stellar model atmospheres. For instance, the same grid of models but using the WMBasic stellar atmospheres (Pauldrach et al., 2002) produced offsets of 0.3 dex towards even lower values of $\eta'$. Besides, models predict a similar dependence on metallicity as in the case of the optical parameter.

As in the case of the optical parameter, models also show a dependence of the mIR parameter on effective temperature, in the sense that higher values of the mIR parameter are associated to lower model effective temperatures. Nevertheless, the position of HII galaxies in this diagram, overlapping a fraction of the data, and the confluence of the different slopes of the fits to the models towards the higher excitation corner of the plot, indicate that this parameter appears less efficient/reliable for those objects with higher ionization degree (i.e. lower [SIll]/[SIV] ratios).

The study of these softness parameters along the radial direction of the discs of spiral galaxies provides a consistent scenario to study the variation of the hardening of the ionizing radiation, mainly because these HII regions have been observed consistently across each galaxy. In Figure 2, we show the deprojected gradient of the optical softness parameter for sets of HII regions in a sample of spiral discs for which the four required emission lines have been measured. In Table 2, we list the bibliographic sources from which we have extracted the data for each galaxy as well as the slopes of the corresponding best linear fits, along with their errors. All of the galaxies show negative or flat radial gradients of $\eta'$ (opt). The values of the slopes ranging from 0.00±0.01 (NGC 1365) to -0.11±0.05 dex/kpc (NGC 598). This result indicates that, besides no radial positive gradient has been found, the existence of strong gradients of the hardening of the ionizing radiation in HII regions of spirals is not an universal property. Rather, it seems that a range of slope values can be defined.

In Figure 3, we show the gradients that were derived using the mIR softness parameter. Although a first impression gives us a large number of observations in this spectral regime, the poorer quality of a major part of the data – mainly due to low signal-to-noise ratio of the [StV] emission
Figure 2. Deprojected radial variation of the optical softness parameter of H\textsc{ii} regions and corresponding best linear fit for a sample of spiral discs. The slopes of the individual fits are listed in Table 2.

Figure 3. Deprojected radial variation of the mIR softness parameter of H\textsc{ii} regions and corresponding best linear fit for a sample of spiral discs. For NGC2403 and NGC5236, solid lines show the fit to the common range with the optical and dashed line the fit to all the data.

Table 2. Slopes of the deprojected gradients of both optical and mIR softness parameters in a sample of spiral disc galaxies.

| Galaxy name | log $\eta$ (opt) | log $\eta$ (mIR) | Ref. |
|-------------|------------------|------------------|------|
| NGC 300     | -0.07±0.03       | –                | B09  |
| NGC 598     | -0.11±0.05       | -0.03±0.01       | V88, R07 |
| NGC 1232    | -0.01±0.02       | –                | B05  |
| NGC 1365    | 0.00±0.01        | –                | B05  |
| NGC 2403    | -0.08±0.02       | -0.07±0.02       | G97, D08 |
| NGC 2903    | -0.10±0.05       | –                | B05  |
| NGC 2997    | -0.03±0.02       | –                | B05  |
| NGC 5194    | -0.03±0.05       | –                | B04  |
| NGC 5236    | -0.03±0.02       | -0.04±0.05       | B05, R08 |
| NGC 5457    | -0.08±0.05       | -0.14±0.02       | K03, G08 |
| NGC 6946    | –                | 0.00±0.01        | D08  |
| Milky Way   | –                | 0.02±0.01        | G02  |

$^a$ B04; Bresolin et al., 2004; B05; Bresolin et al., 2005; B09; Bresolin et al., 2009; D08; Dale et al., 2009; G97, Garnett et al., 1997; G02, Giveon et al., 2002; G08; Gordon et al., 2008; K03, Kennicutt et al., 2003; R07; Rubin et al., 2007; R08; Rubin et al., 2008; V88: Vilchez et al., 1988

line in H\textsc{ii} regions--; precludes this study in a high number of galaxies. The slopes of the linear fits and their errors are also listed in Table 2. As in the case of the optical parameter, we observe two main trends, with a pronounced gradient of the hardening of the radiation in some of the objects but a flat one in some others, as in the case of the Milky Way Galaxy. This behaviour we noted for our Galaxy was derived also by Morisset (2004) using ISO data. A qualitative agreement is seen between both parameters in those galaxies for which they can be measured simultaneously. For instance, both parameters lead to pronounced gradients in M101 and within the common radii of NGC 2403 (the inner 5 kpc have both optical and mIR parameters). On the contrary, both parameters point to a somewhat flat gradients in M83. This agreement appears to reinforce the corresponding presence or absence of gradient in these galaxies. In the case of M63 the agreement between both slopes seems poorer, but still marginally consistent. Unfortunately, given the limitations expressed above for the mIR and the lower number of galaxies analyzed, along this discussion we will use the slopes derived from this parameter only in a qualitative way.

In order to try to understand the possible origin of the gradients derived for the ionizing SED of H\textsc{ii} regions in spiral galaxies, we have studied the correlation between the strength of these gradients and the properties of the disc H\textsc{ii} regions. In principle, one can expect that this relation could be driven by the existence of gradients of the metallicity across the discs. Though metallicity gradients have been derived for all these galaxies giving a range of slopes, we failed to find a clear correlation between the slope of the metallicity gradient (taken from Pilyugin et al 2004) and the corresponding slopes of the gradients of the $\eta$ parameter. This result does not exclude the possible correlation, within a given galaxy, between the softness parameter of H\textsc{ii} regions and their individual abundances (e.g. Vilchez and Pagel 1988; Bresolin et al 2000); it is however clear that, at
the galaxy scale, the strength of the \( \eta' \) gradient seems not to be driven by the metallicity gradient.

We have explored possible driving mechanisms of this behaviour at the galaxy scale. As we show in Figure 4 a significative trend appears to be present between the slopes of the gradients of the hardening of the ionizing radiation –obtained with the optical softness parameter–, and the rotation velocity of the corresponding discs (taken from Pilyugin et al., 2004). This means that the gradient is more pronounced in the slow rotation, less massive galaxies. This fact may be pointing to a link between the evolutionary status of the galaxy disc and the properties across them of the ionizing radiation produced by the massive stellar clusters. A hint in this direction can be seen in the right panel of Figure 4 where the slope of the \( \eta' \) gradient is shown versus the morphological type of galaxies. Again a trend is present in the figure, favouring stronger gradients for later type galaxies.

In this respect, it is necessary to bear in mind that the slopes of the gradients of the hardening of the ionizing radiation could be driven by the star formation properties of the samples of HII regions (e.g. efficiency of star formation) selected in the discs. Overall, this fact would imply that faint/low surface brightness and bright HII regions represent two families of objects that could reflect different stellar temperature behaviours across spiral discs. Thus, contrary to typical (bright) giant HII regions (more frequent in later types), low surface brightness HII regions probably remain less affected by the star formation conditions in the whole discs (see Helmboldt et al., 2009). In turns, this latter kind of HII regions seems more typical in earlier types. This may be the paradigmatic case of the Milky Way, whose flat \( \eta' \) gradient is traced mainly by small HII regions.

In summary, the existence of radial gradients of the hardening of the radiation looks to be real and independently supported in some galaxies by the results coming from the optical and the mIR, but its relation with the mechanisms governing star formation across the discs using HII regions of different luminosities must be further investigated.

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Figure 4. In left panel, relation between the rotation velocity of the spiral discs and the gradients of the hardening of the ionizing radiation as obtained from the softness parameters. In right panel we show the relation between the gradient and the morphological type. Black squares represent the gradients obtained from the optical \( \eta' \) and white squares from the mIR one.