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# Observations for a detailed modelling of Galactic H II regions

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**Summary.** We present some results of an ongoing project aimed at the combined study of massive stars and their surrounding nebulae by means of a detailed study Galactic H II regions ionized by only one massive star. With this, we intend to check the validity of the new generation of massive star model atmosphere codes in terms of ionizing flux distribution. We take into account the effect of the nebular density distribution in our analyses. Various types of stellar and nebular observations have been collected for this purpose; some of them were obtained using ALFOSC at NOT.

## 1 Introduction

The intense far ultraviolet (FUV) radiation emitted by early OB-type stars ionizes the interstellar medium, generating the so-called H II regions. These regions can be used to derive properties of the associated stellar population (e.g. initial mass function, star forming rate, age), and other properties of the galactic region where these are located, such as chemical composition. However, since the properties of H II regions crucially depend on the spectral energy distribution (SED) of the massive star population, and this part of the stellar flux is generally inaccessible to direct observations, the predictions resulting from massive star atmosphere codes are a crucial ingredient.

The outer layers of blue luminous stars are characterized by strong NLTE conditions, spherically extended geometries, and the effect of hundreds of thousands of flux absorbing metal lines present in the FUV and UV spectral ranges (producing the so-called line-blanketing and line blocking effects, as well as the development of radiatively driven stellar winds). All the above effects must be taken into account when modeling the atmospheres of blue luminous stars.

In the last decades, a great effort has been devoted to the development of stellar atmosphere codes of hot massive stars. The advent of the new generation of NLTE, line blanketed model atmosphere codes, either plane-parallel (TLUSTY, Hubeny & Lanz, 1995 [6]), or spherically expanded (FASTWIND, Santolaya-Rey et al. 1997 [18], Puls et al. 2005 [16]; CoSTAR, Schaerer & de Koter 1997 [19]; CMFGEN, Hillier & Miller 1998 [5]; WM-*basic*, Pauldrach et al. 2001 [15]) is already a fact.

This new generation of stellar atmosphere codes, including a more realistic description of the physical processes characterizing the stellar atmosphere, produce quite different ionizing SEDs than the previous plane-parallel, NLTE/LTE, hydrostatic models (Mihalas & Auer 1970 [10], Kurucz 1992 [8], Kunze 1994 [7]). Some notes on this, and on the consequences over the ionization structure of H II regions, can be found in Gabler et al. (1989) [2], Najjarro et al. (1996) [14], Sellmaier et al. (1996) [20], Rubin et al. (1995) [17] and Stasinska & Schaerer (1997) [24]. Although the new predictions seem to walk in the right direction (viz. Giveon et al. 2002 [4], Morisset et al. 2004 [12]), non-negligible differences can be found between the various stellar codes (see e.g. Mokiem et al. 2004 [11], Martins et al. 2005 [9], Puls et al. 2005 [16]).

As commented above, the FUV range of the stellar flux cannot be observed directly; therefore, it is crucial to find indirect tests to constrain it. Ionized nebulae have been many times claimed as potential tools to check the validity of the emergent SED predicted by stellar atmosphere models. However, this study is complicated by the fact that the ionization structure of H II regions also depends on the number and distribution of ionizing stars, the gas distribution in the nebulae, the nebular abundances, and the presence of dust.

## 2 The project

In 1997, Stasinska & Schaerer [24] proposed that the best approach to test the ionizing fluxes of OB-type stars would be to consider simple situations in which the number of free parameters was reduced, considering as many observational constraints as possible. Following this suggestion, we decided to begin a project in which we are performing a very detailed and unprecedented study of a sample of bright Galactic H II regions with simple geometries, and ionized by a single massive star. The main aims of our project are

1. to test the prediction of the new generation of stellar atmosphere codes in the H Lyman continuum (below 911 Å), and
2. to study the effect of nebular geometries other than spherical on the ionization structure of the H II regions,

by means of the combined study of the ionizing stars and their surrounding nebulae. The selected H II regions and their associated ionizing sources are indicated in Table 1.

**Table 1.** H II regions and their associated ionized sources included in our study.

| H II region | Popular name | $d$ (arcmin) | Ionizing star | SpT        |
|-------------|--------------|--------------|---------------|------------|
| M20         | Trifid       | $\sim 13'$   | HD 164492A    | O7.5III(f) |
| IC5146      | Cocoon       | $\sim 11'$   | BD +46 3474   | B1V        |
| S2-112      | ...          | $\sim 15'$   | BD +45 3216   | O8V        |
| M43         | de Mairan    | $\sim 6'$    | HD 37061      | B0.2V      |

### 3 Observational dataset

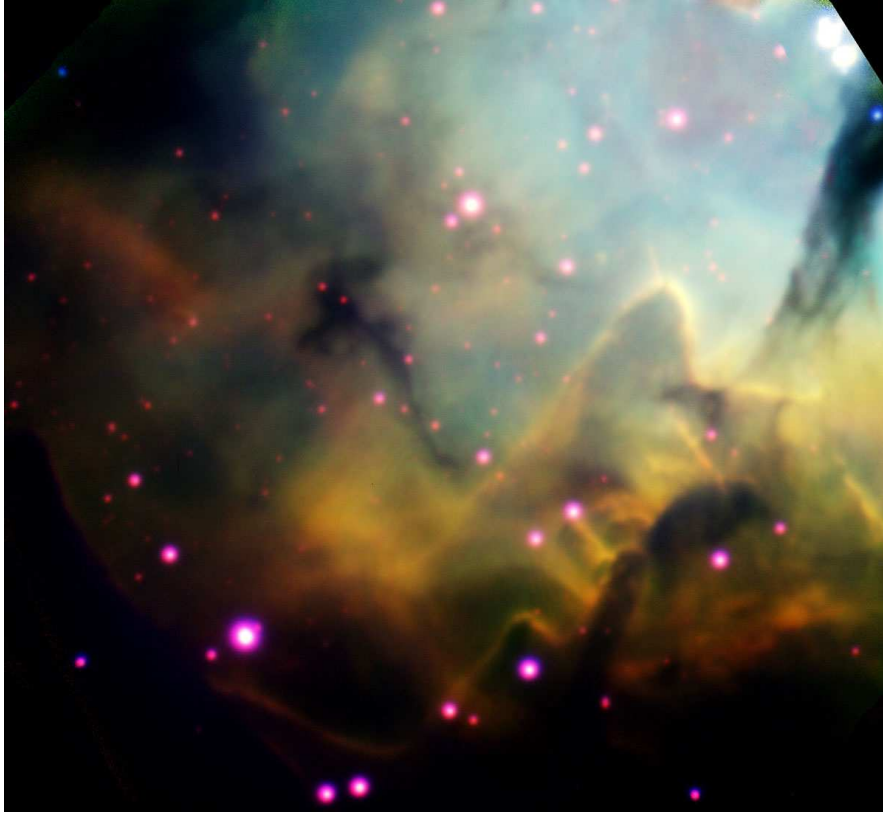
Part of the observational dataset required for this project was obtained during two observing campaigns (2006/04/26-29, and 2006/08/17-19) by using the capabilities offered by the ALFOSC instrument attached to 2.56m NOT. These observations comprise nebular imaging in several narrow-band filters ( $H\alpha$ ,  $H\beta$  and their respective continuum, [O III] and [S II]), along with long-slit medium resolution spectroscopy.

For the later, we used CCD#8, along with grisms #8 and #14. This configuration allowed us to observe the optical, and part of the near infrared spectrum (3300-8350 Å), including  $H\alpha$  and  $H\beta$ , along with other useful He I, [N II], [S II], [S III], [O II], [O III], and [Cl III] lines. In addition, we decided to also use grism #7, that includes  $H\alpha$  and  $H\beta$  lines in the same configuration (very important to estimate the reddening, and put together in the same scale the spectra provided by grisms #8 and #14). Figures 1, 3 and 4 show examples of the narrow-band and spectroscopic results obtained with ALFOSC@NOT.

Since the apparent size of some of the studied nebula is actually larger than the field-of-view of the ALFOSC instrument, additional nebular imaging in the same narrow band filters was obtained with the Wide Field Camera (WFC) at 2.5m Isaac Newton Telescope (INT). Finally, the nebular observations were complemented with medium resolution (R=10000) spectra in the range 4000 – 5000 Å +  $H\alpha$  region of the associated ionizing stars, obtained with the Intermediate Dispersion Spectrograph (IDS) attached to the INT.

### 4 Obtaining useful information from the observational dataset

Many useful information can be obtained from the observational dataset above. We present here the guidelines we are following in our study, illustrated by some preliminary results for the case of the Trifid Nebula (M 20) and its main ionizing source, HD 164492A. We also refer the reader to Simón-Díaz et al. (2005a [21], 2007 [23]), García-Rojas et al. (2005 [3]), and the PhD thesis work by S. Simón-Díaz [22].



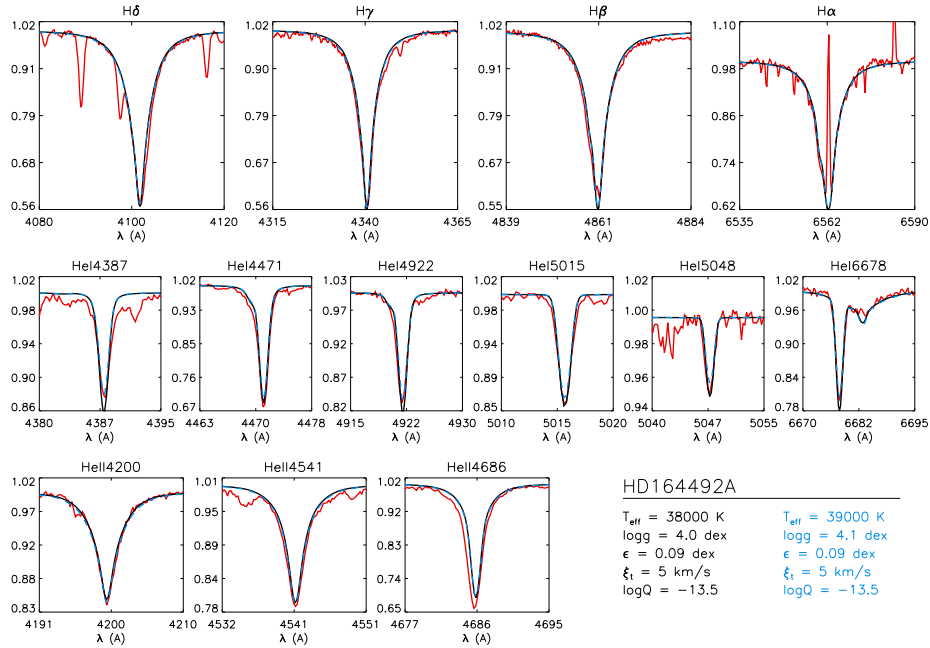
**Fig. 1.** False color image of a central area of the Trifid Nebula, M20, combining data in [O III] (blue),  $H\alpha$  (green) and [S II] (red) obtained with ALFOSC at NOT.

#### 4.1 Stellar spectroscopy

The stellar parameters and the ionizing SEDs of the ionizing stars are obtained by means of detailed analysis of the IDS@INT spectra. To this aim, we are using the new generation of stellar atmosphere codes. The technique is already standard (see e.g. Simón-Díaz et al. 2006), and is based on the visual fitting of synthetic H I, He I and He II optical lines resulting from a stellar atmosphere code to the corresponding observed lines. Figure 2 shows the case of HD 164492A as an example of the quality of the fits.

#### 4.2 Nebular imaging

By using nebular imaging in several narrow band filters we can better understand the nebular gas distribution and the extinction in the H II region. Spatial variations of the extinction inside the nebulae are mapped using flux-

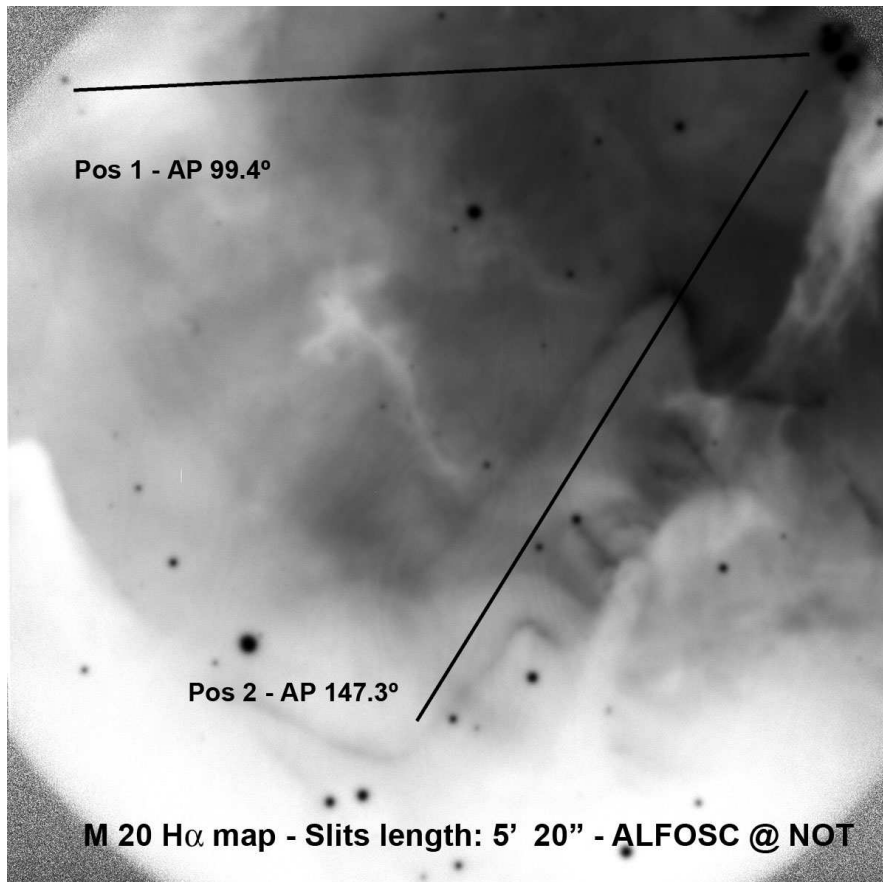


**Fig. 2.** Fitting of FASTWIND synthetic profiles (broadened to  $v \sin i = 45 \text{ km s}^{-1}$ ) to the optical H and He lines of HD 164492A, the main ionizing source of the Trifid Nebula, M20. Two sets of stellar parameters are shown to illustrate the accuracy of the stellar parameters determination.

calibrated and continuum-subtracted  $\text{H}\alpha$  and  $\text{H}\beta$  images. Narrow-band imagery in  $\text{H}\alpha$ ,  $[\text{O III}]$  and  $[\text{S II}]$  allow us to get a detailed knowledge of the ionization structure of the nebula (see Figure 1), that is compared with the predictions obtained with their tailored photoionization models. Flux-calibrated and continuum-subtracted  $\text{H}\alpha$  imaging is used to estimate the total  $\text{H}\alpha$  flux of nebulae and map their surface brightness profiles. The total  $\text{H}\alpha$  luminosity is then compared with the  $\log Q(\text{H}^0)$  obtained for the ionized star in order to check if the nebula is ionization or density bounded. Finally,  $\text{H}\alpha$  images were also used to decide the location of the long-slit in the nebular spectroscopic observations (see Figure 3).

### 4.3 Nebular long-slit spectroscopy

We have selected and observed several slit positions along the nebular radii of each object (see Figure 3, illustrating the case of M20). Several small-sized apertures are extracted from the long-slit observations ( $\sim 5$ -10, depending on the nebula). By using the flux-calibrated spectra from the various apertures we can obtain emission line ratios which allow us to know the variation of the temperature and density along the nebular radius, and the ionization



**Fig. 3.** H $\alpha$  image of a central area of M20 obtained with ALFOSC at NOT. The slit positions used to get the nebular spectroscopic data are shown.

degree of the H II region. In addition, nebular abundances can be derived. These nebular spectroscopic observations can be used as constraints of tailored photoionization models of the various nebulae (see next section). An example of a wavelength- and flux-calibrated spectrum of one of the apertures in M20 is shown in Figure 4.

## 5 Work in progress

All the information extracted from the nebular and stellar observations, and quoted in Section 4, is being used to construct tailored models of the observed nebulae. In addition, nebular spectroscopic observations allow us to impose constraints to the input considered in those models in terms of stellar ionizing SEDs, and nebular geometries other than spherical.



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