Letter to the Editor

Revealing deuterium Balmer lines in H II regions with VLT-UVES

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Abstract. The search for deuterium Balmer lines with VLT-UVES is reported in H II regions of the Galaxy and the Magellanic Clouds. The D I lines appear as faint, narrow emission features in the blue wings of the H I Balmer lines and can be distinguished from high-velocity H I emission. The previous identification to deuterium is re-inforced beyond doubt.

The detection of Dα and Dβ in Orion (Hébrard et al. (2000)) is confirmed and deuterium lines are now detected up to at least D7. The UVES observations provide the first detection of Balmer D I lines in four new H II regions (M 8, M 16, M 20, and DEM S 103 in SMC), demonstrating that these lines are of common occurrence.

Key words: line: identification – ISM: atoms, ions – ISM: H II regions – ISM: individual objects: M42, M8, M16, M20, M17, DEM S 103

1. Introduction

Deuterium is an element of primordial origin. Measuring its abundance in different astrophysical sites brings valuable constraints on the Big-Bang nucleosynthesis and the Galactic evolution (e.g. Lemoine et al. [1999]).

The detection and identification of the deuterium Balmer lines Dα and Dβ in emission in the Orion Nebula was first reported by Hébrard et al. (2000) hereafter Paper I). The narrowness of these lines, their strength with respect to the hydrogen lines and finally their relative fluxes were incompatible with recombination excitation, but could be understood in terms of fluorescence excitation by stellar UV continuum in the Photon Dominated Region (PDR), located behind the ionized region.

Here, observations of the whole Balmer series with the new spectrograph UVES, installed at the Nasmyth focus of VLT-UT2, are presented for Orion and other H II regions. Observations are described in Sect.2. Results for each H II region are presented in Sect.3. New evidence in support to the identification of deuterium is discussed in Sect.4. A more complete analysis will follow in forthcoming papers.

2. Observations

Observations were secured during the night 2000 July 25th-26th, using the UV-Visual Echelle Spectrograph (UVES) located at the Nasmyth focus of Kueyen, the second VLT Unit Telescope (D’Odorico & Kaper (2000). Spectra from both the red and blue arms were registered simultaneously on two detectors, using the standard setting DIC1 (390+564). The approximate spectral ranges were 3290 Å - 4530 Å (blue arm), and 4610 Å - 5620 Å and 5660 Å - 6660 Å (red arm), encompassing the whole Balmer series.

The slits were 8" and 11" long for the blue and red arms respectively. The slit width was 1" on the sky. According to the staff of the VLT, the spectral resolution was $\lambda / \Delta \lambda = 40,000$ (Full Width at Half Maximum, FWHM), equivalent to $\sim 7 \text{km s}^{-1}$. The present conclusions do not depend on the exact value of $\lambda / \Delta \lambda$, which will be determined after reducing the calibration exposures. A total exposure time of one hour was devoted to each H II region (except for Orion, Sect.3.1), the observations being divided in short sub-exposures to prevent detector saturation at the H I Balmer lines.

Data reduction (bias subtraction, flat-fielding, wavelength calibration) was performed with the UVES pipeline, using the available calibration database. 1D spectra were box-extracted from the central third of the slits. The standard sky-subtraction algorithm, inappropriate for extended objects, was omitted. This extraction was judged robust enough for this preliminary study. Subsequent data reduction will be performed over the whole slit length, using the calibration exposures obtained during the observing run.

Cosmetics and bad pixels were cleaned where necessary. Sub-exposures were averaged (no shift was observed from one sub-exposure to the next) and the lines were shifted to the same...
radial velocity. For a given object, the peak fluxes of the different lines were assigned the same value in order to display the relative variations of the weak lines (figures of Sect. 3). Shifts and normalizations were all based on Gaussian fits to the emission lines.

3. Results

Line detections reported here in the blue wings of the H I lines are at least at the 5-σ confidence level. Most of them are confirmed by the detection of lines at the same velocity for several principal quantum numbers n.

3.1. Orion Nebula (M 42)

The area observed in Orion was the same as the one observed previously (Paper I). The slit, oriented North-South, was located 2.5' South of θ¹ Ori C (HD 37022) at coordinates α = 05:35:16.7, δ = -05:25:29 (J2000). The exposure time was 30 min in the red arm and 50 min in the blue arm.

Plots of the H I Balmer line wings are shown in Fig. 1. Deuterium lines are detected from D H to D η (noted H3 to H9) in the Orion Nebula. All H I lines are centered at 0 km s⁻¹ velocity (right dotted line) and are normalized to identical peak intensities (2.1 × 10⁴ on y-scale). The dotted line to the left corresponds to the wavelengths adopted for the D I lines (Table 2). Hζ is blended with He ι.

FWHM are from Gaussian fits, after quadratic subtraction of the instrumental point-spread function. The FWHM of the D I lines is ~ 11 km s⁻¹, much less than that of the H I recombination lines (~ 30 km s⁻¹). Widths similar to these were found for the lines detected in M 8, M 16, M 20 and DEM S 103 (see below). From Fig. 1 it is apparent that D I increases relative to H I for increasing n, at least up to Dc. Approximate relative fluxes are given in Table 1. Despite lower signal-to-noise ratio, a similar trend exists in the data for M 8 and M 16.

Table 1. Preliminary line flux ratios in M 42

| line  | D ν H I | D ν H I | D ν H I |
|-------|---------|---------|---------|
| α     | 2 × 10⁻⁴ | γ     | 7 × 10⁻⁴ | ε     | 10 × 10⁻⁴ |
| β     | 6 × 10⁻⁴ | δ     | 9 × 10⁻⁴ |         |         |

Fig. 2. Same as Fig. 1 for wings of [N ii], [O ii], [O iii] and Hα in Orion (peak intensities 2.1 × 10⁴). Compare to Fig. 7.

3.2. Lagoon Nebula (M 8)

In M 8, the slit was oriented North-South and located 17'' East and 18'' North of Herschel 36 (HD 164740), at α = 18:03:40.8, δ = -24:22:25. This position corresponds to position L11 in Bohuski (1973). Deuterium is detected from Dα to Dζ (Fig. 3). Again the flux ratios range from $F(Dα)/F(Hα) \approx 2 \times 10^{-4}$ to $F(Dζ)/F(Hζ) \approx 1 \times 10^{-3}$.

M 8 was observed at a second slit position: 43'' South from Herschel 36 [position L7 in Bohuski (1973), not shown here]. The coordinates were α = 18:03:40.3, δ = -24:23:27 and the slit was oriented East-West. Only Dα was detected, with a weaker flux: $F(Dα)/F(Hα) \approx 3 \times 10^{-5}$.

3.3. Eagle Nebula (M 16)

In M 16, the slit was oriented North-South and located at α = 18:18:51.7, δ = -13:49:07. It corresponds to one of the brightest regions of the PDR in this nebula. Deuterium is detected from Dα to Dγ (Fig. 4).
The flux ratios range from \( F(D) / F(H) \approx 2 \times 10^{-4} \) to \( F(D') / F(H') \approx 1 \times 10^{-3} \).

3.4. Trifid Nebula (M 20)

In M 20, the slit was oriented North-South and located 51'' East and 23'' South from HD 164492, at \( \alpha = 18\text{h} 02\text{m} 27.3\text{s}, \delta = -23\text{h} 02\text{m} 14\text{s} \). This position corresponds to position T12 in Bohuski (1973). Only Do was detected (Fig. 5).

3.5. DEM S 103 in the Small Magellanic Cloud

The last deuterium Balmer line detection was performed outside the Galaxy, in the brightest H II region of the SMC, namely DEM S 103 [Henize 66, Caplan et al. (1996)]. The coordinates of the slit, oriented North-South, were \( \alpha = 00\text{h} 58\text{m} 51.6\text{s}, \delta = -72\text{h} 10\text{m} 09\text{s} \). Again, only Do was detected (Fig. 5).

3.6. Omega Nebula (M 17): high-velocity structure emission

In M 17, the slit was oriented North-South and located at \( \alpha = 18\text{h} 20\text{m} 48.0\text{s}, \delta = -16\text{h} 10\text{m} 31\text{s} \). Here the emission features detected in the blue wings of the H i lines, from Hα to He (Fig. 6), differ from those shown in previous targets:

- they are broad (FWHM \( \approx 20 \text{km s}^{-1} \), instead of \( \approx 10 \text{km s}^{-1} \), whilst the main H i component has the usual FWHM \( \approx 30 \text{km s}^{-1} \));
- they are proportional to the H i lines (intensity \( \approx 3 \times 10^{-3} \) relative to nearby H i for every \( n \));
- [N II], [O II] and [O III] present clear counterparts at the same velocity (Fig. 7).

It is concluded that, in this case, the features should be mainly due to H i emission from ionized material with velocity \( \approx -70 \text{km s}^{-1} \) relative to the main body of the nebula. The width of these features is compatible with recombination excita-
Since the lines are seen for many members of the Balmer series, they can only be D1 or blue-shifted H1 emission. H1 emission may arise from H+ gas (recombination) or H0 gas (fluorescence). High-velocity ionized structures will produce H1 recombination lines with properties like those already listed in the case of M17 (width, flux, counterparts), not observed in the other HII regions described in Sect.3. A high-velocity neutral structure cannot be formally excluded for any one isolated object, but the probability that such a structure could exist and yet be detectable only in H1 is low. No evidence for the existence of such a structure could be found in the case of Orion (Paper I).

Considering the present data, it would be extraordinary if such a neutral component could be present in such a systematic manner in five different HII regions, always at about the same velocity.

Understandably, the D1 lines are narrow since they arise from a cold material with small thermal velocity. Nonetheless, considering the prevalence of large velocity fields in HII regions, it was not a priori obvious that these lines would appear so systematically narrow (Table 2). The explanation partly lies in the fact that the entrance aperture of UVES is relatively small and that observable HII regions tend to be incomplete on one side, with the associated molecular cloud and PDR located behind the expanding H+ region. This is consistent with the tendency shown by the D1 lines to be redshifted with respect to the H1 lines (Table 2). Thus, in practice, a small line width (at the expected wavelength) turns out to be an important criterion to identify D1. On the other hand, HII regions may exist with PDR’s encompassing a large velocity range. A fundamental criterion for D1 identification remains the lack of counterparts in lines from ionized species. Large variations of the line intensity ratio D1/H1 with n constitute another useful criterion (Table 1), since fluorescence will generally not result in the same decrement as the one corresponding to recombination.

As a result of the present high spectral resolution and high signal-to-noise observations, the identification of deuterium Balmer lines is now very safe.

5. Conclusion

Detection of deuterium Balmer emission in five HII regions is reported. These are first detections in four targets, including an extragalactic one. Detection was made feasible thanks to the large collecting area of the 8.2m VLT mirror and the high efficiency of UVES. Fluorescence is confirmed as the probable excitation mechanism of D1, recombination being excluded. Spectroscopic criteria leading to virtually certain identification of D1 in any given HII region are now clearly established.

Possible ways to determine D/H from D1 Balmer lines were discussed in Paper I. One method requires a knowledge of the n for which the line ratio D1/H1 starts decreasing. The detection of D1 up to D9, and possibly D16, in Orion suggests this as a promising way of investigation. Comparison of D1 to O1 fluorescence lines, present in the UVES spectra and also produced in the PDR, may be another way to explore.

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