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Letter to the Editor

Detection of deuterium Balmer lines in the Orion Nebula*

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Abstract. The detection and first identification of the deuterium Balmer emission lines, Dα and Dβ, in the core of the Orion Nebula is reported. These lines are very narrow, have identical 11 $\mathrm{km\,s^{-1}}$ velocity shifts with respect to Hα and Hβ, are probably excited by UV continuum fluorescence from the Lyman (D I) lines and arise from the interface between the H II region and the molecular cloud.

Key words: line: formation – line: identification – ISM: atoms, ions – ISM: H II regions – ISM: individual objects: M42 – cosmology: observations

1. Introduction

Deuterium is believed to be entirely produced in the Big Bang and then steadily destroyed by astration (Epstein et al. 1976). Standard models predict a decrease of its abundance by a factor 2–3 in 15 Gyrs (e.g., Tosi et al. 1998). This picture is essentially constrained by deuterium abundance determinations at ~ 15 Gyrs (primordial intergalactic clouds), 4.5 Gyrs (protosolar) and 0.0 Gyrs (interstellar medium). Although the evolution of the deuterium abundance seems to be qualitatively understood, the measurements show some dispersion. Thus, absorption in the Lyman series provides interstellar deuterium abundance $(\mathrm{D/H})_{ISM} \simeq 1.5 \times 10^{-5}$ (Linsky 1998), but with fluctuations that may well be real (Vidal-Madjar et al. 1998). These dispersions led to the development of non-standard models in which, for example, deuterium may either decrease by more than a factor 4 in 15 Gyrs (e.g., Vangioni-Flam et al. 1994) or be created/destroyed by new mechanisms [e.g., Lemoine et al. (1999) for a review].

A detailed appraisal of the evolution of deuterium is crucial for cosmology and galactic chemical evolution. The most reliable estimate of $(\mathrm{D/H})_{ISM}$ to date is based on far-UV observation from space (Copernicus, IMAPS, HST or FUSE) of the Lyman lines of D and H in absorption. These lines are also observed in the optical and near-UV to obtain D/H in high redshift quasar absorbers. Other D/H determinations include *in situ* measurements in the Solar System (e.g., Mahaffy et al. 1998), observations of molecules such as HD or DCN (e.g., Bertoldi et al. 1999) and observations of D I 92 cm (e.g., Chengalur et al. 1997).

New methods to determine D/H are of interest. One possibility is ground-based observation of the deuterium lines. The isotope shift of the deuterium Balmer lines with respect to the hydrogen Balmer lines is $-81.6\ \mathrm{km\,s^{-1}}$. These D I lines have never been identified before. Attempts to detect Dα in absorption in the Sun (Beckers 1975) and early-type stars (e.g., Vidal-Madjar et al. 1988) were unsuccessful (D is destroyed in stars). Traub et al. (1974) observed Hα in the Orion Nebula using three-etalon Fabry-Perot spectrometers and reported D/H upper limits.

Here we report on spectra of Orion, secured at the Canada-France-Hawaii Telescope (CFHT). Emission lines detected in the blue wings of Hα and Hβ are identified with Dα and Dβ. A preliminary account was presented by Hébrard et al. (1999). Observations are described in Sect. 2, the identification and the origin of the lines in Sect. 3 and 4 and the excitation mechanism in Sect. 5.

2. Observations, data reduction and results

Observations of the Orion Nebula (M 42, NGC 1976) were conducted at the 3.6m CFHT, using the Echelle spectrograph Gecko at the Coudé focus with a slit length of $\sim 40''$. The Hα and Hβ spectral ranges were observed in October 1997 and September 1999 respectively. For Hα, the entrance slit was 1.2mm wide (3.5$''$ on the sky), providing a resolution $R = \lambda/\Delta\lambda \simeq 40\,000$ ($\sim 7.5\ \mathrm{km\,s^{-1}}$); the detector was the 2048×2048 "Loral 5" thin CCD and the spectral range was 6544Å - 6576Å. For Hβ, the slit was 0.8mm wide (2.3$''$) leading to

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* Based on observations collected at the Canada-France-Hawaii Telescope, Hawaii, USA.

$R \simeq 50\,000$ ($\sim 6\ \mathrm{km\,s^{-1}}$); the detector was the 2048×4500 "EEV2" thin CCD and the spectral range was 4832Å - 4885Å.

The slit was centred 2.5′ South of θ^1 Ori C (HD 37022), the brightest star of the Trapezium. The slit orientation was slowly rotating during the exposures (Coudé focus). Totals of 4.5 and 1.5 hours were devoted to Hα and Hβ respectively, divided in 30 – 45 min sub-exposures. Small rotations of the grating were applied between Hα sub-exposures in order to disclose ghosts that may depend on grating setting. Hα was also observed at higher resolution ($R \simeq 80\,000$) in the same area for 20 min. Finally, Hβ was observed 2.5′ North and 20″ South of θ^1 Ori C with shorter exposures and $R \simeq 50\,000$. Bias, flats and Thorium-Neon lamp calibration exposures were secured regularly during the observations for each instrument configuration.

The spectra were reduced using MIDAS software. The steps of the data reduction were as follows: (1) bias subtraction; (2) flat division; (3) bad pixel and cosmic cleaning; (4) summing the rows to transform the 2D-spectra into 1D-spectra; (5) wavelength calibration; (6) shift to the heliocentric frame; (7) alignment of the different sub-exposures; and (8) suming up of the sub-exposures. After shifting to the heliocentric frame, both Hα and Hβ were fitted by a Gaussian on each sub-exposure. The standard deviation of the Gaussian peaks was less than $1\ \mathrm{km\,s^{-1}}$. Sub-exposures were shifted to the average peak before summation in order to preserve the spectral resolution. An interfering signal, instrumental in origin, appeared in the Hβ spectra, producing small oscillations in the dispersion direction, which slightly increased the noise level. Wavelengths are determined to better than $1.5\ \mathrm{km\,s^{-1}}$ and $1.0\ \mathrm{km\,s^{-1}}$ in the Hα and Hβ final spectra respectively.

Two weak emission lines are obvious in the blue wings of Hα and Hβ (Fig 1). Anticipating the conclusion of Sect. 3, the weak lines are already identified with Dα and Dβ in Table 1, where results of Gaussian fits to Hα, Hβ, Dα and Dβ are given. The full widths at half maximum (FWHM) of the deuterium lines are much smaller than those of the hydrogen lines. Relative fluxes (last row of Table 1) are based on the theoretical Hα/Hβ ratio, thus implicitly correcting for reddening. For an H$^+$-weighted electron temperature $(0.85\pm0.10)\times10^4$K and electron density $\sim 5\times10^3$ cm^{-3} (e.g., Esteban et al. 1998), the Case B recombination ratio $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ is 2.91±0.03 (Storey & Hummer 1995). Departure of this ratio from Case B is expected to be much less than 1% in this thick nebula for any reasonable dust content (Hummer & Storey 1992).

Dα and Dβ are seen all along the 40″ slit. Dβ is present at all three positions. The velocity shifts between Dβ and Hβ at 2.5′ N, 20″ S and 2.5′ S of θ^1 Ori C are respectively 11.8, 9.1 and 10.0 $\mathrm{km\,s^{-1}}$ and the Dβ fluxes 4.2 ± 1.1, 2.3 ± 0.6 and 5.7 ± 1.1 (Hβ= 10 000).

3. Identification of Dα and Dβ

According to Table 1, the shift of both weak lines with respect to the hydrogen lines is $-71\ \mathrm{km\,s^{-1}}$ whereas the isotopic shift of

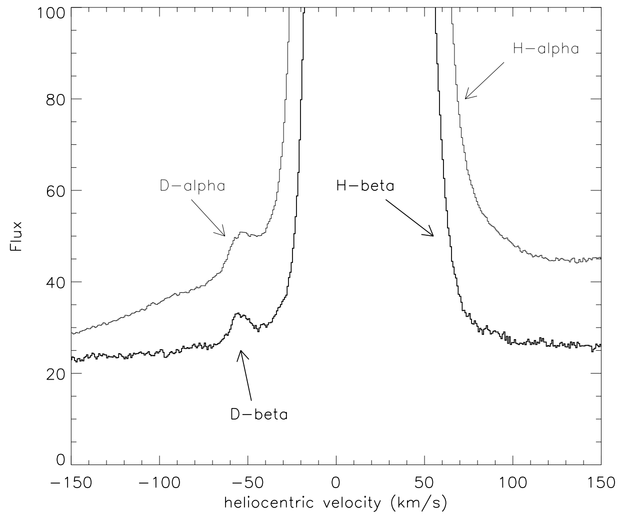

Fig. 1. Vicinity of Hα and Hβ in Orion, showing Dα and Dβ in emission. The x-axis is in $\mathrm{km\,s^{-1}}$ relative to the rest wavelength of either Hα or Hβ. The vertical scale corresponds to peak fluxes 7250 and 2500 for Hα and Hβ respectively. Then $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ = 2.91 and $I(\mathrm{D}\alpha)/I(\mathrm{D}\beta) \simeq 1.10$.

deuterium is $-81.6\ \mathrm{km\,s^{-1}}$. This significant difference forces us to consider alternative possibilities.

• Spectral artifact? No feature equivalent to these lines is present in either the red wings of Hα and Hβ or the wings of [N II] λ6548.05Å, observed simultaneously. Small rotations of the grating applied between sub-exposures resulted in no change in profile, position and intensity of the lines. Finally no such lines were detected in bright planetary nebulae we observed in September 1999 (Hébrard et al. 2000), using the same instrument. This also excludes possible sky-line emission. In fact, no sky-lines have been reported at these wavelengths. Thus, these lines are real features, specific to the Orion Nebula.

• Unidentified process or element? Attempts to find other identifications were unsuccessful. These lines cannot be scattered stellar emission [for example, Hα from θ^1 Ori C is variable (Stahl et al. 1996)], as lines from hot stars are broad. For the same reason, they cannot be Raman features. The wavelengths do not correspond to any known quasi-molecular line. The fact both lines have identical velocity shifts with respect to H I practically restricts the possibilities to H I and D I emission (no He II is detected in the Orion Nebula).

• High-velocity hydrogen emitting structure? Traub et al. (1974) reported the detection of a line in the blue wing of Hα. This line may correspond to ours, although it was interpreted by these authors as high-velocity H I emission, noting the existence of a similar component in [O III] (Dopita et al. 1973). Indeed, our $R = 80\,000$ spectrum shows a blue component in [N II] but with velocity shift only $\sim -22\ \mathrm{km\,s^{-1}}$. More importantly, *any component arising from the* H II *region should have a minimum width corresponding to thermal broadening*. The thermal FWHM for hydrogen at 8500K is 20 $\mathrm{km\,s^{-1}}$, much larger than 8 $\mathrm{km\,s^{-1}}$ (Table 1). The $-22\ \mathrm{km\,s^{-1}}$ ionized hydrogen emission should be lost in the Hα and Hβ wings.

Table 1. Gaussian fitted line profiles

Line identification	Hα	Dα	Hβ	Dβ
Rest wavelength (Å)	6562.796	6561.010	4861.325	4860.003
Observed wavelength (Å)	6563.12 ± 0.03	6561.59 ± 0.03	4861.60 ± 0.02	4860.44 ± 0.02
$v_\odot$ ($\mathrm{km\,s^{-1}}$)[a]	14.8 ± 1.5	26.5 ± 1.5	17.0 ± 1.0	27.0 ± 1.5
FWHM ($\mathrm{km\,s^{-1}}$)[b]	32.0 ± 0.5	8.6 ± 1.0	32.1 ± 0.5	8.1 ± 1.5
Relative flux[c]	$29\,100 \pm 300$	6.3 ± 0.6	$10\,000 \pm 200$	5.7 ± 1.1

[a] Heliocentric velocity.
[b] Full width at half maximum corrected for instrumental width (original FWHM: 32.9, 11.4, 32.7, 10.1 $\mathrm{km\,s^{-1}}$ respectively).
[c] Using the theoretical $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ (see text), then $I(\mathrm{D}\alpha)/I(\mathrm{D}\beta) = 1.10 \pm 0.22$.

Nonetheless, the fluorescence mechanism proposed below to explain the D I line excitation (Sect. 5) may a priori apply to H I as well. One cannot formally exclude H I fluorescence emission from a neutral, cold (thermal FWHM is $\sim 7\ \mathrm{km\,s^{-1}}$ at 10^3 K), high-velocity ($-74\ \mathrm{km\,s^{-1}}$ LSR), low velocity dispersion ($<< 10\ \mathrm{km\,s^{-1}}$) layer keeping the same kinematical properties over many arc minutes. However this is very unlikely as this hypothetical structure should in addition have a small column density (no other fluorescent line is seen at that velocity) and lie sufficiently close to the Trapezium stars (fluorescence varies as the inverse square of the distance to the continuum source). The survival of a neutral thin shell against photoionization (no low-ionization material is interposed; see Sect. 4) is also in question. As a matter of fact, Cowie et al. (1979) detected several components of high-velocity gas in absorption against ι Ori (a star located within half a degree of the region we observed), notably a component at $-68\ \mathrm{km\,s^{-1}}$, close to $-74\ \mathrm{km\,s^{-1}}$. According to these authors, this component corresponds to a very old highly ionized supernova remnant situated over 100 pc from the Trapezium, at any rate too far away to yield fluorescence.

It can therefore be safely concluded that these lines are Dα and Dβ. Kinematics (Sect. 4) brings out one more fundamental piece of evidence.

4. Origin of the lines

In the Orion Nebula, the H II region is essentially matter bounded toward the observer and radiation bounded in the opposite direction (e.g., Rubin et al. 1991). The narrowness of the D I lines implies that they must originate in a cold, localised region along the line of sight, that is behind the H^+ region, in the "Photon Dominated Region" (PDR) where deuterium is in atomic form.

This is borne out by available information on velocities. The heliocentric velocity of the D I lines is $\sim 27\ \mathrm{km\,s^{-1}}$ compared to $\sim 16\ \mathrm{km\,s^{-1}}$ for H I. In a blue spectrum of the Trapezium region (Kaler et al. 1965), the Si II lines 3856+63Å, probably produced by fluorescence in the PDR, appear shifted by +11 $\mathrm{km\,s^{-1}}$ relative to the neighbouring H I Balmer lines, a shift similar to the one found for Dα and Dβ. Over a region close to the one we observed, Esteban & Peimbert (1999) measured heliocentric velocities 6.4±1.4, 14.0±2.0, 24.6±2.2 and 26.8±1.4 $\mathrm{km\,s^{-1}}$ for Ar^{++}, H^+, O^0 and N^0 respectively, tracing the free expansion of the H II region, moving away from the molecular cloud. Over the same region, Hänel (1987) found 20-23 $\mathrm{km\,s^{-1}}$ for [N II] [in agreement with our measurement v([N II]) $\simeq 21\ \mathrm{km\,s^{-1}}$] and 23.5–28 $\mathrm{km\,s^{-1}}$ for [S II], thus encompassing the velocity we found for Dα and Dβ. From millimeter and submillimeter observations, Hogerheijde et al. (1995) found velocities $\sim 28\ \mathrm{km\,s^{-1}}$ for different molecules. Observations thus clearly imply that the D I lines could arise from the boundary of the H II region.

5. Fluorescent excitation of Dα and Dβ

The narrowness of Dα and Dβ allows the possibility to be excluded that the lines are excited by recombination in an ionized gas (Sect. 3). The H^0 column density of the PDR is $\sim 10^{22}\mathrm{cm}^{-2}$ (Tielens & Hollenbach 1985), so the D^0 column density is $\sim 10^{17}\mathrm{cm}^{-2}$ [assuming a typical $(\mathrm{D/H})_{ISM} \simeq 10^{-5}$] and the optical thickness in, e.g., Lyβ_{D} is over 100. Since the D I emission is confined to a layer coincident in velocity with that of the PDR (Sect. 4) and since the dust opacity there is orders of magnitude less than the Lyβ_{D} opacity, fluorescence from the Lyman lines is a viable process to produce the deuterium Balmer lines.

The UV continuum is dominated by θ^1 Ori C, whose effective temperature is close to 4×10^4K (Rubin et al. 1991). Let us assume that both the ionization of the H II region and the deuterium fluorescence are due to a 4×10^4K black body and that half the ionizing photons escape from the H II region in the matter bounded directions (Rubin et al. 1991). If each photon impinging on the PDR at the Lyβ_{D} wavelengths ultimately produces a Dα photon by scattering on D^0, and only Lyβ_{D} photons lead to Dα excitation (neglecting cascades), then the flux ratio $I(\mathrm{D}\alpha)/I(\mathrm{H}\alpha)$ is about $1.5 \times 10^{-4} \times (\Delta v/5\mathrm{km\,s^{-1}})$, where Δv is the full velocity width of the zone where Dα is effectively excited. According to Tielens and Hollenbach (1985), the turbulent pressure in the PDR corresponds to $\Delta v \simeq 5\ \mathrm{km\,s^{-1}}$ and according to Table 1, Δv is probably less than 8 $\mathrm{km\,s^{-1}}$. The rather good agreement of this very coarse estimate with the observed value 2.2×10^{-4} (Table 1) is fortuitous. This estimate may be wrong in different ways. Many Ly$_{\mathrm{D}}$ lines can a priori absorb primary photons and feed Dα by cascades, then leading to an overestimation. Conversely, part of the Ly$_{\mathrm{D}}$ photons are absorbed by dust and/or reflected back to the H II region. Also, our estimate is global in character and our particular line of sight may not intercept identical fractions of the H II region and the PDR. Most importantly, the stellar continuum may be depleted in the vicinity of the Ly_H lines, particularly for the first members of the series. Nonetheless, since these different effects tend to partially compensate one another, the above agreement indicates that the assumption of UV continuum fluorescence leads to the correct order of magnitude for the Dα flux.

Unlike Dα/Hα, the flux ratio Dα/Dβ is little sensitive to aspect effects. Assuming a ratio of visual extinction to column density of hydrogen nuclei $A_V/N_{\rm H} = 5{\times}10^{-22}$ mag cm^2 and $A_{FUV}/A_V = 5$ (Tielens and Hollenbach 1985), the ratio of Ly$\beta_{\rm D}$ opacity to dust opacity is $\sim$ 240. Only for large principal quantum numbers should dust absorption decrease D I fluorescence (the photoexcitation cross section goes roughly as n^{-3}). Since the stellar continuum should be about flat over the Lyman line range (except possibly in the vicinity of strong lines), some insight into the excitation process can be gained by assuming that all $Ly_{\rm D}(n)$ lines, with principal quantum number n up to some given n_0, convert identical numbers of UV photons by fluorescence and that no fluorescence occurs for $n > n_0$. Then, working out the cascades, the theoretical Dα/Dβ flux ratio is about 1.28, 1.41 and 1.51 for $n_0 =$ 4, 5 and 6 respectively and tends to level off for larger n_0's. Only for $n_0 = 4$ is this simple description compatible with the observed value 1.10 ± 0.22 (Table 1). Since one would expect that a relatively large number of $Ly_{\rm D}$ lines should contribute to the excitation, the suggestion is that one of the above assumptions was oversimplified or some significant process has been overlooked. For example, the stellar continuum is probably depleted in the wings of the $Ly_{\rm H}$ lines and the vicinity of Ly$\beta_{\rm H}$ is likely to be most affected, then selectively reducing the Dα emission. Observing higher deuterium Balmer lines is essential before attempting any detailed modeling.

Note that the Dα/Dβ of Table 1 was obtained assuming that the reddening correction was the same for the H I and D I emitting zones. If extinction internal to the nebula is significant, then the actual (de-reddened) Dα/Dβ ratio will be even smaller since the PDR, where the D I lines come from, is more deeply embedded than the H II region.

Dust absorption will dominate $Ly_{\rm D}$ fluorescence for sufficiently large n, the deuterium Balmer decrement then changing from very flat to very steep. This break can lead to a D/H value inasmuch as the dust opacity per hydrogen nucleus is known. On the other hand, fluorescence lines from species co-extensive with D^0 including O I and Si II can provide independent information on the primary continuum flux and on the competition of line scattering with dust absorption for photons. O I fluorescence lines have been detected long ago in Orion and the excitation process was established by Grandi (1975). O I lines may lead to a D/O abundance ratio. Detailed observations and proper modeling of many deuterium Balmer lines and Comparing D I and other fluorescence lines appear as a potentially accurate means to determine D/H in H II regions.

6. Conclusions

Deuterium is identified for the first time in a nebula from optical spectroscopy. The excitation mechanism of the observed lines, Dα and Dβ, is continuum fluorescence from $Ly_{\rm D}$ lines in the PDR. Considering the saturation of the first $Ly_{\rm D}$ lines and the possible influence of the neighbouring $Ly_{\rm H}$ lines, observing the full deuterium Balmer series is essential to obtain a D/H value from optical data and appears feasible, at least in Orion.

An optical determination of D/H in H II regions would allow to check existing $({\rm D/H})_{ISM}$ values and obtain D/H in low-metallicity extragalactic H II regions, where the deuterium abundance should be close to its primordial value.

The large photoexcitation cross section of the first Lyman lines makes deuterium Balmer fluorescence a sensitive way to detect deuterium in nebulae, leading for example to stringent upper limits to D/H in planetary nebulae (Hébrard et al. 2000), where deuterium is depleted.

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