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Deuterium Abundance in the Interstellar Medium: A Search for Deuterium Balmer Lines in the Orion Nebula and Iota Herculis

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The results of a search for deuterium Balmer lines in the Orion Nebula and the slowly rotating B star Iota Herculis are reported. Due to artifacts in the spectrum of Orion our search for deuterium is largely inconclusive, but we are able to approximate an upper limit for D/H. The spectrum of Iota Herculis shows a low signal-to-noise ratio and a number of telluric lines near the position of the deuterium-alpha line, inhibiting detection of possible deuterium absorption. We attempt a number of filtering techniques to clean the spectra, but further analysis is required to determine the success of these methods.

I. Introduction

The abundances of certain light elements are sensitive indicators of the baryonic mass density during the first 100 to 1,000 seconds following the Big Bang: in particular, the abundance of deuterium (D) relative to hydrogen (H) is such an indicator. Standard Big Bang Nucleosynthesis (SBBN) models assume an isotropic and homogeneous universe and predict the ratio of D/H to decrease as the baryon-to-photon ratio (η) increases. For greater η, the D/H ratio exhibits a rapid drop-off in favor of He^4 (Tytler et al. 2000). Little deuterium, if any, has been created since the Big Bang took place (Reeves et al. 1973, Pasachoff & Vidal-Madjar 1989). Deuterium is normally recycled into heavier elements in the processes of stellar nucleosynthesis. This is called astration. Thus, for a certain D/H ratio and a given estimate of how much processing has occurred over time, it is possible to extrapolate a primordial value for D and, subsequently, a value for η.

The determination of D/H for the interstellar medium (ISM) has been a continuing pursuit, not only because of its cosmological implications, but also in hopes of determining the galactic gradient of D/H. An accurate D/H ratio could provide valuable insight into the evolution of the Galaxy. A study of Sgr A and Sgr B near the Galactic Center of deuterated molecules finds an unusually high D/H ratio, $(1.7 \pm 0.3) \times 10^{-6}$, for a region with tremendous amounts of stellar processing (Lubowich et al. 2000). It is inferred that this higher than expected abundance is due to a recent infall of low-metallicity gas. A study looking at the Orion Nebula published positive results in a search for Balmer deuterium lines (Hébrard et al. 2000a). However, due to the UV fluorescence process for exciting deuterium Balmer lines, it was difficult to establish a D/H ratio. These results were later confirmed by Hébrard et al. (2000b).

Although deuterium is astrated in most stellar atmospheres due to convective actions and mass transfers, in slowly rotating early type stars the stellar exteriors are not subject to the same environments, and the deuterium abundances should equal those of the ISM out of which the star formed.

In this study, we present the results of a search for deuterium Balmer lines in the spectra of Iota Herculis and the Orion Nebula.

II. Observations and Reduction

Observations were made on three separate occasions: August 1999, December 1999, and March 2000. All data were acquired on the Pierce-McMath Telescope at Kitt Peak operated by National Solar Observatories. The data were acquired by a professional observer for Profs.

Donald Lubowich (Hofstra and American Institute of Physics) and Jay M. Pasachoff (Williams College). A Milton and Roy grating (hereafter M&R) with a 180-mm transfer lens was employed to give a dispersion of 2.7 Å mm^{-1} and a resolution of 60,000. An echelle grating was also employed with an 180 mm transfer lens to give a dispersion of 1.53 Å mm^{-1} and a resolution of 100,000. The August observations primarily concentrated on Iota Herculis (HD 83206) in the wavelength range of Hα, a slowly rotating B star with a periodic pulsation (section III). December observations surveyed the Orion Nebula at 15 arcseconds West of HD 37022 (θ^1 Ori C), 15 arcseconds South, 2.5 arcminutes South, and centered East/West in the nebula in the wavelength range of Hα and some over the wavelength regime of Hβ. March shared observations between Orion and Iota Herculis. The data were unbinned with the exception of two days in March (17, 18), which were binned by 5.

We carried out the following data reduction during my Keck Summer Fellowship. The data were extracted using standard procedures from the Image Reduction and Analysis Facility (IRAF). The data were first overscan corrected and bias subtracted, then flat-fielded, all using CCDPROC in IRAF. The one-dimensional spectra were extracted using APALL in IRAF with a broad aperture, approximately 90% of the width of the two-dimensional spectra, and summed across the aperture at each wavelength. APALL applied a 3rd order spline polynomial function to trace the spectra over the full wavelength range. August 20 produced unusable spectra due to poor weather conditions. The Hβ spectra from December 21 are poor and unusable for uncertain reasons. The spectra were then wavelength calibrated using thorium-argon comparison lamps. Both Iota Herculis and Orion were co-added in various combinations which will be discussed in section III. Certain co-adds of Iota Herculis were normalized to the continuum level (section III) using a no greater than 3rd order spline polynomial.

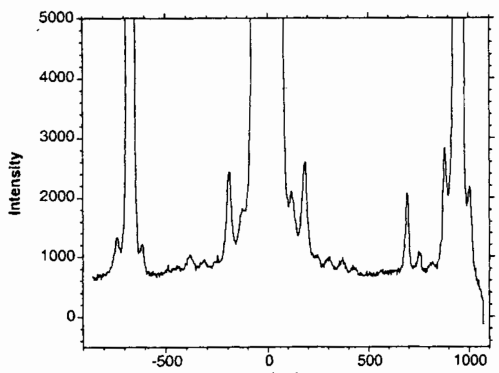
III. Results and Analysis

A. Orion

Throughout the M&R grating results a series of symmetric ‘bumps’ appear around Hα and the two NII lines λ6548 Å and λ6583 Å (Fig. 1). These features also appear in Hβ. The features are evident in all positions in the M&R grating results. However, the ‘bumps’ do not appear on the spectra obtained with the echelle grating (Fig. 2). The difference of observations between the two gratings' spectra suggest that these features are not physical occurrences native to Orion but are artifacts caused by the particulars of the M&R grating setup.

The largest of the ‘bumps’ in the M&R grating, looking at 2’.5 South of HD 37022, is at a velocity of approximately -68 km/s from the center of Hα, corresponding to the velocity shift of an emission reported by Hébrard et al. (2000a), looking at the same position in Orion, to be Balmer Dα emission. Hébrard et al. conclude this feature is deuterium emission produced by UV continuum fluorescence from Lyman (DI) lines. We have limited echelle spectra in this position (March 14) which show no evidence of this emission. These results have been confirmed by Hébrard et al. (2000b) in Orion up to at least Dη in addition to the detection of Balmer DI lines in four other HII regions.

The artifacts in the Orion data make it impossible to determine if Dα is evident at the expected position of –81.6 km/s (1.8 Å blueshifted) from the center of Hα because this position is occulted by one of these artifacts. The same problem exists in Hβ, as the expected position for Dβ is 1.2 Å blueshifted from Hβ. The echelle data from December 21 were combined and no evidence of Dα is found. The Orion data from December 21, acquired with the echelle grating,



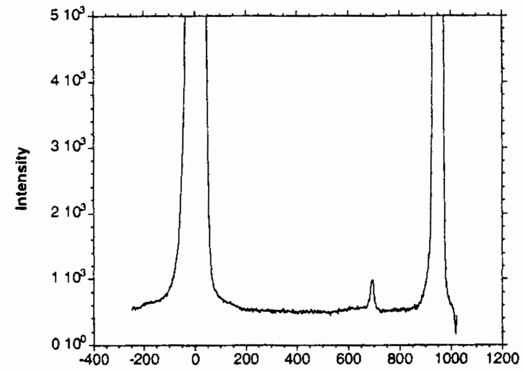


Figure 1 (left) shows the symmetrical 'bumps' that appear around Hα and the two NII lines using the M&R grating. The velocity scale is zeroed at the center of Hα, as determined by a gaussian fit. This is 15" West of HD 37022. Figure 2 (right) shows a spectrum of 15" West of HD 37022 using the echelle grating. Hα is at 0 km/s. Note the lack of symmetrical 'bumps' around Hα and the NII line.

is an average of 9 x 1800 sec (4.5 hrs) spectra in the position of 15" West of HD 37022. An approximate signal-to-noise ratio (S/N) of the December 21 data is established by averaging the continuum noise level and summing over twice the full width at half maximum of Hα. We then divide the integrated flux of Hα by the total noise. We find that S/N = 5,900. This yields D/H $\leq 1.7 \times 10^{-4}$, in agreement with previously determined values for D/H which, on average, are D/H $\approx 1.5 \times 10^{-5}$ (Jenkins et al. 1999).

B. Iota Herculis

Iota Herculis is a slowly rotating B star which exhibits complex changes in the line profiles on timescales of 1.5 hrs to 113 days (Mathias & Waelkens, 1995). As our data are from three different runs (including the data from Spaulding & Galloway 1994), from several months or years apart, there would be a high degree of error in fitting all the data under a single periodic curve. Unfortunately, there does not seem to be an adequate number of observations in a given observing run to analyze the period in a smaller timeframe.

The spectrum of Iota Her shows a relatively sharp absorption line of Hα with a full width at half maximum of 41.4 km/s for a 16.4 hrs normalized combination of the data from March 14, 17, and 18 and August 17 and 21 (7 x 1800 sec; 2 x 1500 sec, 750 sec, 700 sec, 600 sec, 6 x 540 sec; 540 sec, 2 x 600 sec, 5 x 800 sec; 10 x 1800 sec; 8 x 1800 sec listed respectively). The existence of a Dα line is difficult to establish due to the telluric lines which may occult the position of the potential line.

We attempt several different procedures for eliminating the telluric lines. We employ a gaussian filter technique, a simple line removal technique, and dividing the Iota Herculis spectrum by a fast-rotating B star's spectrum. Unfortunately, none of these methods are successful.

These attempts at removing telluric lines incite an approach of avoiding the data with telluric lines in the expected position of Dα. While this method works at the cost of data, it allows us to avoid the problem of telluric line removal altogether. The telluric lines are isolated based on the comparison of different spectra at different periods of the line profile pulsation (i.e. the Hα wavelength will fluctuate while the telluric lines remain stationary on a day-to-day comparison). We document the wavelength of the telluric lines using an IDL script, and the spectra that do not have telluric lines in the vicinity of Dα are shifted so that the center of Hα is at 6562.0 Å, determined via a Gaussian fit, and co-added. The aforementioned 16.4 hrs spectrum of Iota Herculis is the product of this combining method. We find the resulting signal-to-noise to be ~ 800. This value is too low to determine if Dα is present and sets a high upper limit on D/H, since it is impossible to separate noise from a low intensity absorption line.

IV. Conclusions

We find that due to artifacts in the spectra, most likely from the grating used, a large amount of Orion data must be discarded in the search for deuterium Balmer lines. However, using the data acquired with the echelle grating we have established an upper limit of D/H $\leq 1.7 \times 10^{-4}$. This result is consistent with other observations of D/H in the ISM. If the problem with the grating system can be corrected or substituted entirely for echelle spectroscopy, it may be possible to detect deuterium in Orion and verify the observations of Hébrard et al.

The observations of Iota Herculis do not yield evidence of deuterium Balmer lines. Given the relatively high number of hours observed (16.4) and the resulting low signal-to-noise (~800), it seems unlikely that deuterium lines will be discovered in Iota Herculis by our methods, even if telluric lines are carefully avoided in the positions of deuterium Balmer lines. However, the verification of Iota Herculis as having periodic shifts in its line profiles and the study of its periodicity have their own merits. A more careful study, incorporating the spectra we have, may prove to be an interesting project that could shed light on the stellar physics at work in Iota Herculis. Also, with further work and employing different techniques, it still may be possible to detect deuterium Balmer lines in the stellar atmosphere of a B star.

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