The Search for Deuterium: CCD-aided Spectral Analysis of B-type Stars

Will Best (Haverford student visiting Williams College)
Tanya Ramond (Bryn Mawr student visiting Williams College)
Sean Sandys (Williams student sponsored by NSF grant)
advisor: Jay M. Pasachoff, Williams College

We analyzed CCD images of echelle spectra to investigate the abundance of deuterium in the upper atmosphere of slowly-rotating B-type stars. The data were taken at Kitt Peak National Observatory in May 1992. The spectra did not show deuterium within experimental uncertainties, and we set a tentative upper limit at $D/H < 2 \times 10^{-5}$. To test that we were properly co-adding scans and that no systematic contributions to noise were present, we investigated the relationship between exposure time and signal-to-noise ratio for CCD images. We found that the signal-to-noise increased with the square root of exposure time, in agreement with theory. Signal-to-noise levels of over 800:1 were achieved with exposures up to ~ 22 hours on third-magnitude stars.

Introduction

Big Bang theory predicts the formation of deuterons during the era of nucleosynthesis, 100 to 1000 seconds after the Big Bang. Among nucleons created during nucleosynthesis, deuterons are the only type not also produced by later astrophysical processes. Any deuterium visible today was, therefore, created shortly after the Big Bang (Pasachoff and Fowler, 1973, 1988). Furthermore, deuteron formation at that time was particularly sensitive to the density of baryonic matter in the universe. Deuterons fused with free protons to form $_3$He nucleons; if more protons were present, then less deuterons remained afterwards. Thus, the abundance of deuterium in the Universe will yield the amount of baryonic matter, by comparison with models (Vidal-Madjar and Gry, 1984). The deuterium abundance in today's visible Universe could thus help determine whether the Universe is open or closed, and provide clues about the amount and evolutionary significance of baryonic matter.

Deuterium is brutally difficult to observe; the relative abundance of deuterium to hydrogen (hereafter D/H) lies well below 10^{-4}. Thus, the search for deuterium has also spawned a search for the best method of detection. Previous attempts have focused mainly on the interstellar medium. Radio searches for simple deuterated molecules (where a deuterium atom replaces ordinary hydrogen) indicate D/H varying between 2×10^{-4} and 2×10^{-6} (Pasachoff and Fowler, 1973, 1988). A lengthy search for the 92-cm spin-flip spectral line (analogous to the 21-cm line for hydrogen) culminated in the announcement of an upper limit on D/H between 3×10^{-4} and 2×10^{-5}. Observations of the ultraviolet deuterium Lyman-α line have given a D/H measurement between 3×10^{-5} and 8×10^{-6} (Pasachoff & Vidal-Madjar, 1989).

The lack of consistency among these results has encouraged further searches, including ours. We looked for deuterium at visible wavelengths in atmospheres of stars in which boron had been detected. Boron burns in stellar interiors; thus most stars have no visible boron content because atmospheric mixing transports all the boron initially present in the atmosphere down to the interior. However, recent models predict only a small amount of mixing in hot, early-type stars (Mazzitelli and Moretti, 1980); elements present in the upper atmosphere should therefore remain there throughout the hydrogen-burning phase of the stars' lives. Therefore, in stars where boron is still visible in the spectrum, deuterium should also be present. We assume that the density of deuterium is constant throughout the Universe; if a little deuterium has been consumed in a given star, the model can predict this. A value for the D/H ratio in stars can be extrapolated to find a value for the entire Universe, and can be used to verify the accuracy of current stellar models.

To accomplish our goal, we had to substantially improve the signal-to-noise ratio (hereafter SNR) of previous spectra taken of our object stars. Most data have SNR ~30:1; we hoped to achieve at least 500:1, using IRAF 2.9 to reduce the CCD data. Theory predicts that the SNR increases with the square root of exposure time; we verified this relation in our data to assess possible systematic sources of noise and to test our reduction procedure.

Method

F. Crawford, J. Partan, and J. M. Pasachoff, took the CCD spectral images on 12-18 May, 1992, at Kitt Peak, in collaboration with D. Lubowich. They used the 0.9 meter Coudé feed telescope, and a 832 x 832 CCD camera. Echelle spectra of visible wavelengths, including the region surrounding the Balmer Hα line (6562.80Å), were taken. To increase the SNR, the echelle grating was moved periodically to smooth out pixel-to-pixel variations. Using IRAF, we reduced these data for SNR and looked for the Balmer Dα line (located at 6561.01Å, in the blue wing of the Hα line). Because of the low D/H ratio, we did not expect to find the deuterium line, but intended to set a new upper limit on D/H.

Three slowly-rotating B-type stars were observed (the slow rotation ensures sharp spectral lines):

Name	RV	Type
τ Her	-14	B5 IV
ι Her	-20	B3 V
67 Oph	-4	B5 Ib

(where RV indicates radial velocity, in km/s)

We used the *echelle /newimred* package in IRAF 2.9 to reduce the images. After initial image processing with *ccdproc* (to properly incorporate biases and flatfields),we subtracted scattered light from the images using *apscatter*. We then extracted five "apertures" (spectral orders on the echelle spectrum), including the Hα aperture and two on either side, using *apall* and *apsum* procedures. We calibrated the images in wavelength with *ecidentify*, *ecreidentify*, and *refspec*. The final step in the wavelength calibration was *ecdispcor*, run separately on the images of each of the three stars, in order to achieve the same wavelength solution for all the images of a given star. The separate wavelength-calibrated images could then be added together to increase the SNR.

We measured the SNR with *splot*. Various numbers of spectral images (the majority of which had exposure times of thirty minutes) were added using *combine* to get composite images of varying exposure times; these images were examined to determine how SNR changes with exposure time. To obtain flat regions in which to measure the SNR most accurately, we fit a curve to the continuum level in each of the apertures using *eccontinuum*. For each star, about six to eight sets of SNR measurements were made.

The search for a deuterium line began with the perusal of composites of all exposures for each of the three stars. In addition, we examined continuum-normalized images.

Results and Discussion

The Hα line is so broad in the 67 Oph images that the Dα wavelength falls on the steepest part of the inner Hα wing; trying to find a faint line there is very difficult and error-prone so no substantial conclusions can be drawn. Images of τ Her and ι Her are more suitable for a search for Dα, because the Hα wings are much flatter. We are correcting for the radial velocities of the stars to obtain the shifted wavelength for Dα. The stacked scans for the nominal radial velocities show no evidence of deuterium at the calculated positions in τ Her or ι Her; any potential Dα line was indistinguishable from surrounding noise to a limit of D/H of 2×10^{-5}. But the stars are nonradial pulsators, and we are now working to take into account the hour–by–hour variations in radial velocity and restacking the data. Also, one of us (TR) has worked with Dr. F. Spite at the Observatoire de Paris at Meudon, France, on a theoretical model for the deuterium line in B stars with different deuterium abundances.

Figures 1 and 2 are plots of the SNR versus exposure time. (Though the signal strength depends on atmospheric seeing at observation time, for many exposures time is a reasonable approximation to the signal growth.) In each graph, the solid line is a power fit to the data points, while the dotted line is the theoretical square-root relationship, starting at the value for a single half-hour exposure (this value has the largest uncertainty). For τ Her, the exponent for the data fit curve ranges from 0.37 to 0.53, and the mean exponent is 0.47; The highest SNR achieved was 808:1, with a total exposure time of 1285 minutes. For ι Her, the exponent ranges from 0.28 to 0.48, with a mean exponent of 0.37. The highest SNR for ι Her is 663:1 for a total exposure time of 645 minutes.

The SNR investigation showed that we benefit nicely from the long exposure times on the CCD camera. The SNR values for the τ Her apertures are in very good agreement with the predicted behavior. Six out of nine τ Her SNR fits lie within 0.05 of a perfect fit exponent of 0.50, and most of the curves have the same shape as the theoretical square-root curve. The ι Her data does not conform to theory as closely. The exponents of the data curves are, for the most part, ~0.30, an error of 40.0%. However, it is worth noting that the perfect square-root-fit curves were calculated using the first data point (for a thirty minute exposure time), which is not the best indicator of the behavior of the curve. An average of the SNR of each of the single exposures might work better as a starting point. The other ι Her SNR tests have acceptable fits.

Overall, the data appear to support the theory that for CCD images, SNR increases with the square root of exposure time. We exceeded the goal of a SNR of ~500:1 for twelve out of the seventeen spectral regions for which we used the *splot* function to measure SNR in τ Her and ι Her. We have thus succeeded in significantly improving the quality of the spectra over previous SNR levels. We may safely conclude, therefore, that increasing the exposure time as much as possible continues to be useful and that our reduction procedure is accurate. We now look forward to the result of our stacking, after correction for the varying radial velocities.

Acknowledgments

We would like to thank the following people for their assistance: Jeannette Barnes, NOAO; Daryl Wilmarth, NOAO; Barb Madden, Williams College; Kevin Forkey, Williams College; and last but not least, Jay M. Pasachoff, Williams College. Will Best and Tanya Ramond were supported by a grant from the Keck foundation. Sean Sandys was supported by NSF grant #AST 9014889 and benefited from NSF grant ATM–9005194.

References

Lubowich, D. A., Anantharamaiah, K. R. and Pasachoff, J. M. (1989). "A Search for Localized Sources of Non-Cosmological Deuterium Near the Galactic Center," *Astrophys. J.* **345**, 770-775.

Mazzitelli, I., Moretti, M. (1980). *Astrophysical Journal* **235**, 955.

Pasachoff, J. M., and Fowler, W. A. (1974). "Deuterium in the Universe," *Scientific American* **23**, 108-118.

Pasachoff, J. M., and Fowler, W. A. (1988). Comments on "Deuterium in the Universe," *Particle Physics in the Cosmos*.

Vidal-Marjar, A., and Gry, C. (1884). *Astron Astrophys.* **138**, 285.