UNIVERSITY COLLEGE LONDON

University Of London Observatory — 1B30 Practical Astronomy

Hydrogen in the Interstellar Medium

1 Introduction

Hydrogen is by far the most abundant element in the Universe; by observing hydrogen we trace the distribution of the bulk of normal (baryonic) matter. Much of the hydrogen exists as neutral atomic gas in the interstellar medium of galaxies. The distribution of hydrogen in the galaxy must be observed in order to understand the physics, chemistry and dynamics of the interstellar medium.

In this experiment, the student uses a spreadsheet package (EXCEL) to calculate the predicted shape and strength of the interstellar Lyman-alpha (Ly-α) absorption line. By comparing the theory with observations, made with the *International Ultraviolet Explorer* (*IUE*) satellite, of several distant O stars, the total amount of neutral hydrogen along the lines of sight to the stars can be determined.

Interstellar dust causes the reddening of starlight, which can be measured by the colour excess, $E(B-V)$. The relationship between dust and gas in the ISM can also be investigated by examining the correlation between the amount of hydrogen and the reddening along many lines of sight.

2 Interstellar Hydrogen Lines

Hydrogen can be detected and measured in several ways, but the most sensitive indicator of neutral atomic hydrogen is the *Lyman series* of absorption lines arising from the lowest level (ground state) of the atom. The strongest line in the H I spectrum is Lyman-α, which results from the $n = 1 \rightarrow 2$ resonance transition of the hydrogen atom, and which lies in the ultraviolet region at 1215.67Å.

The interstellar Ly-α line is invariably totally saturated (*i.e.*, no residual flux) at the line centre, and almost always lies on the so-called damping part of the curve of growth. The damping wings of the line arise simply from the natural line width, which is normally negligible, but which becomes important because the H columns are always large. (A 'column' represents the total amount of gas along the line of sight to a star; the *column density*, N, is a way of describing the amount of gas along the column, expressed as the number of particles per square centimetre.) The total column can therefore be determined relatively simply, just from the shape of the observed line wings. Because we are considering natural widths (not pressure broadening) the line profile is independent of gas temperature and density, but depends only upon the column density, N (N has units of cm^{-2}).

We show this as follows. The optical depth is given by

$$\tau(\Delta\nu) = \frac{\pi e^2}{m_e c} f N(\mathrm{H}^0)\phi(\Delta\nu), \tag{1}$$

where $\Delta\nu$ is the frequency measured with respect to the line centre, e and m_e are the electron charge and mass, c is the speed of light, f is the oscillator strength, and ϕ is a function describing the shape of the line profile (in general, a Voigt function).

The profile function for natural broadening is

$$\phi(\Delta\nu) = \frac{\gamma/\pi}{\gamma^2 + (\Delta\nu)^2}, \tag{2}$$

where γ is called the *damping constant.* For Ly-α we have $\gamma = A_{21}/4\pi$, where the Einstein A coefficient is of order $A_{21} \simeq 10^8$, so $\gamma \simeq 10^7 \mathrm{s}^{-1}$. By comparison, $\nu_0 = 2.5 \times 10^{15}\,\mathrm{s}^{-1}$, so in the line wings we certainly have $\Delta\nu \gg \gamma$, and hence, to good approximation,

$$\tau(\Delta\nu) \simeq \frac{\pi e^2}{m_e c} N f \frac{\gamma/\pi}{(\Delta\nu)^2}. \tag{3}$$

Since we normally work in wavelengths rather than frequencies we rewrite this as

$$\tau(\Delta\lambda) = \frac{\pi e^2}{m_e c} N f \frac{\gamma/\pi}{(\Delta\lambda)^2} \frac{\lambda_0^2}{c}. \tag{4}$$

Putting in numerical values ($f = 0.4162$ for Ly-α), we obtain

$$\tau(\Delta\lambda) = 4.257 \times 10^{-20} N/(\Delta\lambda)^2, \tag{5}$$

where $\Delta\lambda = \lambda - \lambda_0$ (in Å) and $\lambda_0 = 1215.67$. The theoretical line profile, $I(\Delta\lambda)$, is then calculated from:

$$I(\Delta\lambda) = I_0(\Delta\lambda) \exp[-\tau(\Delta\lambda)], \tag{6}$$

where $I_0(\Delta\lambda)$ is the residual intensity in the photospheric *continuum* at $\Delta\lambda$, in the absence of any Ly-α absorption.

3 IUE spectra

The rectified, normalized *IUE* spectra for study in this exercise have been prepared as charts in an EXCEL spreadsheet. To access the file containing these data, click on the `H in ISM` shortcut on the desktop of any Windows PC. This will open the read-only spreadsheet file `h_ism.xls`. You can save your results into your own named directory on the `Win-apps ...` network drive, in the tree `1b30\student`. Ask a demonstrator for help in setting up this directory if it does not exist.

The spectra supplied show the Ly-α region in the 12 O-type stars listed in Table 1. The spectra are given in charts on separate sheets, and can be selected by clicking on the tab giving the HD number of the star. The first two sheets of the spreadsheet (called `model` and `final`) are to be used for the calculation of the model line profiles, described in §4.

Examine the spectrum of HD1337. The spectra show a very complicated combination of narrow absorption features together with broad distorted emissions and shifted absorptions characteristic of hot stellar winds. For example, the N V lines at 1231, 1235Å in HD 1337 are Doppler blue-shifted by several Ångstroms from their emission peak near 1245Å. For comparison between model and observed data, and because these spectra are so complicated, the photospheric continuum has been determined elsewhere, and the spectra adjusted such that the level of the continuum residual intensity, $I_0(\lambda)$, is unity; hence, in equation (6), $I_0(\Delta\lambda) = 1.0$. Superimposed on the stellar spectrum is absorption due to neutral interstellar hydrogen gas, the Ly-α line.

4 Model calculations

You will use the spreadsheet and equation (6) to calculate model Ly-α absorption profiles for different values of the column density, N.

Table 1: Photometry of the O stars

HD number	V	$B-V$	$U-B$	Spectral Type
1337	6.14	-0.13	-0.97	O9 IIInn+O9 III
14633	7.46	-0.21	-1.09	O8 V
37041	6.39	-0.09	-0.93	O9.5 Vep
47839	4.66	-0.25	-1.07	O7 Ve
53975	6.48	-0.10	-0.99	O8 V
57060	4.98	-0.15	-1.01	O7e+O7:
57061	4.40	-0.15	-0.99	O9 Ib
57682	6.43	-0.19	-1.04	O9 V
60848	6.87	-0.20	-1.12	O8 Vpe
66811	2.25	-0.26	-1.11	O5 Iaf
93521	7.06	-0.27	-1.08	O9 Vp
175754	7.04	-0.07	-0.97	O8f

Before starting the model calculations, select the `model` sheet, and enter your name and the date; then save the spreadsheet into the named folder in `1b30` $\mapsto$ `student` $\mapsto$ `yourname` on the `Win-Apps ...` network drive. (As you work through this exercise, you should regularly save your results, in case of program crashes, *etc.*)

To begin with, you will have to decide what range of wavelengths you need, how many wavelength points to use, and what values of N to try. To help you on your way, all the stars in this experiment have $19.0 \leq \log_{10} N \leq 22.0$. You should choose a reasonable spacing in $\log_{10} N$ (0.5 is too coarse; 0.05 is too fine) and reasonable values of $\Delta\lambda$ (Å). To decide the wavelength spacing and range, inspect some of the *IUE* spectra and note the extent of the Ly-α profile and how its shape changes from star to star — you do not want a grid so coarse that important structure in the profile is missed; but neither should you default to using so fine a grid that several hundreds of data points are required.

Perform your model calculations on the sheet named '`model`'. Different values of N (and/or $\log_{10} N$) should go in the columns, and wavelength values in the rows.

It is *very important* that you structure your results as follows:

1. Actual wavelength values (*i.e.*, λ, not $\Delta\lambda$) should be given in column B of the spreadsheet. (Therefore, you might wish to use column A for $\Delta\lambda$.)

2. The first wavelength value should be in cell B5; and there should then be no empty cells between the first and last wavelength values.

3. The results for the first model (*i.e.*, for the first value of N) should be in column C; the model calculation for the first wavelength value should then be in cell C5.

4. Other models (for other values of N) should appear in each successive column after column C (*i.e.*, there should be no empty columns between the first model results and those for the highest values of N).

Note that once the basic formula for calculating $I(\Delta\lambda)$ has been entered correctly, all calculations can be made by copying that formula (using the 'fill handle' at the bottom right corner of the selected cell or region). Hence, it should be easy to modify the models to adjust the spacing in wavelength or $\log_{10} N$, should that appear to be necessary when you inspect the model profiles for the first time. (Note that the models on this sheet only need to be generated once and then applied to all stars; refinements to obtain more precise results are done using a smaller set of models, as described below.)

5 Profile analysis

Having calculated a grid of models, you can plot the models on the observed data in order to determine the 'best-fit' value of $\log_{10} N$ for each star.

1. First select the sheet displaying the *IUE* spectrum for HD 1337. Use the custom button '`Plot all models`' to overplot all the models on the stellar spectrum. By inspection, decide which model gives the closest match to the profile of the hydrogen absorption-line (for some stars, you may find the short- and long-wavelength wings of the profile are matched best by different models, because of errors in the continuum rectification). (It might be helpful to note that the data series number is given when the cursor is moved over a line; but take care — series 1 is the *IUE* spectrum, hence model 1 appears as series 2, *etc.*)
2. The model plots can be removed at any time with the '`Remove all models`' button.
3. Once you have made an initial estimate of which model matches the data best, you should refine your result: the first time only, copy all the columns up to and including the first three models to the sheet labelled '`final`'. To refine the result for each star, you can then adjust the values of $\log_{10} N$ on this sheet to generate three models for a 'final fit' to the data: one value of $\log_{10} N$ representing the best match to the data, and two values either side of this to represent the uncertainty (in other words, models for higher and lower values of $\log_{10} N$ which, it could reasonably be argued, still *just* match the data).
4. Use the '`Plot final models`' button to plot (or re-plot) the data after each adjustment until a satisfactory match is achieved.

Carry out the above procedure for all 12 stars, modifying the three models in '`final`' as necessary, and record your final value of $\log_{10} N$ and its uncertainty for each star. Comment on difficulties encountered in individual cases.

In your report, as well as giving your results for $\log N$, you should present a one-page printout (or two pages maximum) version of your entire model calculation results (shrink to fit to pages as necessary), and three sample plots of your 'final fits': one star with a low value of N, one intermediate, and one high. Each plot should show three models: your best-match model and upper and lower limits to show the uncertainty.

6 Interstellar gas and dust

In Table 1, the observed magnitude and colours of each star are given in the *UBV* system. Interstellar dust gives rise to selectively greater absorption of blue light with respect to red light from distant stars. At large distances in or near the galactic plane, all stars are reddened by this effect.

6.1 The correlation between $\log N(\mathrm{H})$ and $E(B-V)$

Many astronomical investigations have led to the conclusion that the intrinsic (unreddened) colours of *all* O stars are given simply by

$$(B-V)_0 = -0.30, \tag{7}$$

to a very good degree of accuracy.

For each star in Table 1, calculate the colour excess $E(B-V)$, where

$$E(B-V) = (B-V) - (B-V)_0. \tag{8}$$

Plot a graph of $\log_{10} N$ versus $E(B-V)$ from your results. If gas and dust are closely associated, the graph should be a line with a tight correlation (little scatter). If they are unconnected, the graph should show only a random scatter and no trend. Briefly describe your results in terms of the degree of correlation you have found.

6.2 The density of interstellar clouds

It is useful to know the density of the interstellar medium, in order to obtain accurate models of the chemistry and physics of interstellar clouds. Along the lines of sight studied here, atomic hydrogen is the most abundant particle; the average density of the interstellar gas along the line of sight can be obtained by dividing the column density of hydrogen (in cm^{-2}) by the distance to the star (in cm).

Most of the neutral hydrogen gas exists in discrete interstellar clouds embedded in lower-density material occupying most of the volume of interstellar space. Dense clumps of material in the line of sight can be identified by the detection of molecular hydrogen, H_2, since this molecule can only form where the cloud is sufficiently dense; the fraction of hydrogen locked in H_2 is an indicator of the cloud density.

Q1: (*a*) Towards the star HD 53975, the amount of molecular hydrogen along the line of sight has also been measured from ultraviolet observations of the absorption spectrum, and has been found to be $\log N(\mathrm{H_2}) = 19.23$. What is the total column density of hydrogen atoms contained in both atomic and molecular hydrogen towards this star? What fraction of the hydrogen atoms towards this star is in the form of H_2? (Remember there are *two* hydrogen atoms per molecule.)

(*b*) Assuming that for HD53975 the absolute magnitude $M_V = -5.0$, calculate the distance to the star and obtain the mean space density (number of atoms cm^{-3}) for interstellar hydrogen. You must use the form of the distance modulus formula which allows for visual extinction, A_V, by interstellar dust. (See ref. 1; you can also find there how A_V can be calculated from the colour excess, $E(B-V)$. Note that one parsec $= 3.09 \times 10^{18}$ cm.)

The line of sight towards another star, HD 110432, passes mainly through one discrete interstellar cloud. Towards this star, $\log N(\mathrm{H\,I}) = 20.85$ and $\log N(\mathrm{H_2}) = 20.68$.

Q2: (*a*) What is the total column density of hydrogen atoms contained in both atomic and molecular hydrogen towards HD 110432? What fraction of the hydrogen atoms towards this star are in the form of H_2?

(*b*) Assuming the distance to HD 110432 to be 300 parsecs, calculate the mean space density of hydrogen towards this star.

(*c*) The angular diameter of the cloud can be estimated by observations of the radio emission from other molecules within it, such as carbon monoxide (CO). Also, by estimating the distance of the cloud, we can get an idea of its true size. Assuming the depth of the cloud along the line of sight to be 10 parsecs, calculate the mean space density of H atoms in the cloud.

Q3: Comparing your results for HD 53975 and HD 110432, comment on the differences between the distribution of interstellar material along these lines of sight.

7 References

1. Zeilik & Gregory, *Introductory Astronomy and Astrophysics*, 4th edition, section 11.4B, p.231.

Author of this version: Steve Fossey (with thanks to Prof. I. D. Howarth for providing the *IUE* spectra).
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