Very Large Hydrogen Atoms in Interstellar Space

David B. Clark
Pennsylvania College of Technology, 1 College Avenue, Williamsport, PA 17701

An interesting question for students studying the H atom spectrum and the Bohr theory is: What is the maximum "observed" size of the H atom as deduced from recorded spectral data? The search for an answer leads into the exotic terrain of interstellar space where H atoms much larger than amoebas exist!

The Bohr theory is inadequate as a general theory of atomic structure, but, as Haendler (*1*) has pointed out, it deserves treatment in chemistry courses due to its intrinsic value and its vital connection to modern quantum mechanics. It works extremely well for the H atom and predicts the spectral lines very accurately. It is especially applicable in astronomical studies since H atoms constitute the overwhelming majority of atoms in most stars and in interstellar space.

When the H atom electron drops from an outer orbit n_0 to an inner orbit n_i, the wavelength λ of the resulting emission line is given by the empirically derived Rydberg equation (which is precisely explainable by the Bohr theory):

$$1/\lambda = R_H(1/n_i^2 - 1/n_0^2) \quad (1)$$

where R_H (the Rydberg constant for hydrogen) = 1.0967758 × 10^{-2} nm^{-1}. For the readily observable Balmer series of lines (in the visible region of the spectrum), $n_i = 2$; thus,

$$n_0 = [4\lambda R_H/(\lambda R_H - 4)]^{1/2} \quad (2)$$

and the wavelength of a Balmer line permits determination of the orbit (n_0) from which the transition originates. After calculating n_0 for a Balmer line and rounding to the required nearest integral value, the Bohr radius r for the excited H atom can be obtained from

$$r = 5.29(n_0^2) \text{ nm} \quad (3)$$

Douglas and von Nagy–Felsobuki (*2*) and Hollenberg (*3*) have described simple experiments that permit students to observe the first eight Balmer lines for H using readily available spectrophotometers. Using the shortest wavelength line reported for Hollenberg's experiment (3798 Å, or 379.8 nm), eq 2 gives n_0 = 10.03. Performing the required rounding to n_0 = 10, eq 3 gives r = 529 nm. Here is easily obtainable evidence for the H atom with a radius 100 times larger than the ground state value. More sophisticated measurements provide evidence for larger H atoms. Herzberg (*4*) presents Balmer spectra in which the first 16 lines can be distinguished, evidence for the H atom with n_0 = 18 for which r = 1714 nm, 324 times the ground state size.

Lab spectra can produce only a relatively small number of Balmer lines. As n_0 increases much above 18, the emission lines get very close together, and pressure broadening ensures that they become indistinguishable. Thus even under high-vacuum conditions, it is difficult to produce a laboratory H atom spectrum showing distinguishable Balmer lines much above n_0 = 18. Eddington (*5*) shows a Balmer spectrum of the chromosphere of the sun containing about 30 distinct lines, proving that we can "observe" extraterrestrial H atoms with n_0 = about 32, but he comments that even under good vacuum conditions H atoms cannot become much larger than this because of crowding, the excited atoms become "entangled" with nearby atoms. Lab conditions cannot provide both an extremely high vacuum and sufficient numbers of H atoms to produce a large number of observable and distinguishable spectral lines. Thus we look beyond the earth to the surfaces of stars in our search for larger H atoms.

Stellar surfaces contain immense amounts of hydrogen at very low pressure and can thus provide many distinguishable Balmer lines. Astronomers label the higher lines "H*X*", where *X* is the number of the line in the Balmer series (e.g., the H9 line is produced by the n = 11 to 2 transition). The spectrum of Beta Lyrae (*6*) clearly shows Balmer lines for almost all transitions up to H21, and Abell et al. (*7*) show the H40 Balmer line in the spectrum of the star HD 193182. Here we can experimentally "observe" the H atom at n_0 = 42 and r = 9332 nm, 1764 times larger than ground state. But, to observe truly large H atoms, we must turn to the extremely diffuse gas regions of interstellar space and abandon the Balmer series in favor of radiofrequency recombination spectra.

In the interstellar gas regions (nebulae) known as HII, most of the H atoms are ionized to form an extremely diffuse plasma of free electrons and protons. The particle density is so low that many electrons can travel great distances before being trapped by a proton, and the "recombined" electron can fall into a very high quantum number Bohr orbit (n_0), thus momentarily forming a very large H atom before dropping to an inner orbit (n_i). If n_i = 2, a Balmer line results, but, if $n_i = n_0 - 1$ (for very high n values), a radiofrequency photon is emitted. Astronomers label such transitions "H*Y*α", where $Y = n_0 - 1$ (e.g., the H90α line is produced by the n = 91 to 90 transition). Kardashev (*8*) suggested in 1959 that these transitions between orbits of very high n values should be detectable in the radiofrequency spectrum. Whereas adjacent Balmer lines at very high n blend into a continuum and cannot be distinguished, quite a few adjacent high-n recombination lines can easily be distinguished since the radiofrequency separation of these lines is large.

Many such radiofrequency recombination transitions have been observed since 1959, enabling astronomers to calculate parameters such as free electron densities and temperatures in many nebulae. For example, studies have been made of the Rosette and North American Nebulae (*9*), the Carina Nebula (*10*), and the Cygnus-X region (*11*) by recording the H166α line that occurs at a frequency of 1425 MHz. And Batty (*12*) has observed the H252α line near 408 MHz in the Carina and other nebulae, originating from regions where the calculated free electron density is as low as 70 per cm^3. Here is the H atom observed undergoing the transition n = 253 to 252, providing experimental evidence that the radius of the H atom in interstellar space can reach 3.39 × 10^5 nm or 0.339 mm! An atom of this size should be (theoretically) visible to the unaided eye.

What is the upper limit to the spectroscopically observable size for the H atom? Assuming a lower limit of 10 MHz in the radio window of the earth's atmosphere, an earth-bound radiotelescope could theoretically detect an interstellar H869α line at 10.00368 MHz for an H atom of r = 4.00 mm. But the adjacent lines (H870α and H868α) would differ by only 0.034 MHz from the H869α line, and line broadening could cause these lines to be "smeared" into indistinguishability. Could an extraterrestrial radiotelescope of appropriate dimensions and sensitivity perhaps detect H atoms the size of a dime ($r = 9$ mm) producing the H1303α line at 2.969 MHz? Such huge atoms would live only in interstellar regions of unimaginably low particle density, and their detection (if they exist) would perhaps be entirely conjectural.

Introducing these very large H atoms in a chemistry class provides a novel and interesting illustration of the interdisciplinary use of the Bohr theory. It is satisfying to see that the old Bohr H atom continues to command considerable respect, at least in deep space where it is truly a dominant and giant figure.

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