search & discovery

Do young stars blow bubbles or dig tunnels as they age?

"Early type stars blow bubbles in the interstellar medium," assert John Castor, Richard McCray and Robert Weaver of the Joint Institute for Laboratory Astrophysics and the University of Colorado in a recent paper[1] in *Astrophysical Journal Letters*. These bubbles are seen as arising when the strong wind emanating from a star sweeps up the surrounding interstellar gas and compresses it into a shell. After a million years, such a bubble would have a radius of 30 parsec with a shell, about 4 pc thick, that expands at about 20 km/sec. While this theory is supported by a variety of observational data, it is being compared with an earlier theory postulating hot interstellar tunnels, which explains some of the same data—some of it apparently with greater accuracy.

Bubbles provide a possible explanation for the uv spectroscopic data brought back by the *Copernicus* astronomical satellite. In particular, they explain the presence of OVI ions (O^{5+}), the absorption lines of which were studied by Edward Jenkins and Debra

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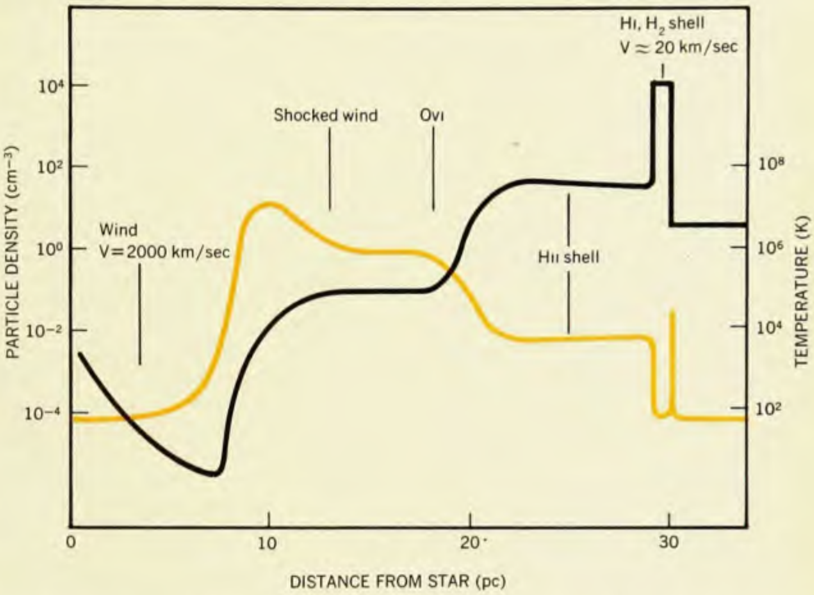


The radial dependence of density (black line) and temperature (color) in a typical structure surrounding a star after about 10^6 yr, according to calculations of Castor, McCray and Weaver.

Highly excited atoms excite interest in many labs

"Since I'm an atom as big as bacterias
I've got to take microwaves serious.
No matter what I do, I'll be cryin'...
After they hit me, I'll be an ion."

So begins a poem written last year by Peter Koch of Yale, during the stresses of preparing his PhD thesis. With James Bayfield, Koch had been studying highly excited atoms (often called "atoms in high Rydberg states," or even simply "Rydberg atoms"); the interesting behavior of such atoms has become the subject of current experimental and theoretical work at many centers around the world.

The unusual properties of these Rydberg atoms (some of which have been prepared with principal quantum number n as high as 105) arise because of their large size and small ionization potential. With electron orbital radii approaching 10^{-5} cm, such atoms are, as Koch's poem suggests, the size of simple bacteria, and they therefore have very large geometric collision cross sections. Because these high states lie so close to the continuum, ionization potentials become very low; when n exceeds about 25, the ionization potential falls to less than 25 millielectron volts. When left to itself, a Rydberg atom has a relatively long lifetime, increasing roughly as n^3, for a fixed orbital angular-momentum quantum number l. Yet even thermal collisions can transfer enough energy to ionize the atom. On the other hand, it also appears possible that a neutral could pass through a Rydberg atom without causing serious perturbation.

As well as the intrinsic interest generated by such systems, there are applications of these studies in radioastronomy (for example, hydrogen transitions involving atoms with n up to more than 250 have been observed in interstellar regions), possibly for laser-induced isotope separation, and for basic atomic physics such as the determination of fundamental constants to improved accuracy.

A session on collisions of Rydberg atoms was organized as part of the Ninth International Conference on the Physics of Electronic and Atomic Collisions, held last July at the University of Washington in Seattle, and papers have been appearing in *Physical Review Letters* and elsewhere this past August and September.

The first modern work on highly excited atoms was reported by A. C. Riviere and D. R. Sweetman (Culham, UK) in 1963, when they extended their technique developed earlier for molecular hydrogen ions to investigate the Rydberg states of hydrogen atoms excited with n up to 23.

When an atom sees an externally applied electric field, the potential-energy surface of the electron–nucleus system is distorted so that there may be a region outside the atom with potential equal to or lower than the potential of one or more of the bound electrons. Then tunnelling of an electron through the potential barrier to the continuum will occur if the tunnelling time is short compared to the lifetime of the bound state. This condition is met for the long-lived high Rydberg states in moderate fields, and Riviere and Sweetman (and many other experimenters since) have used this "field-ionization" method to detect Rydberg atoms. They studied highly excited hydrogen atoms formed by electron capture on protons accelerated to 25–100 keV; the ionizing field was of the order 10^5 volts/cm, strong enough to ionize atoms with n greater than 9 in 10^{-10} sec.

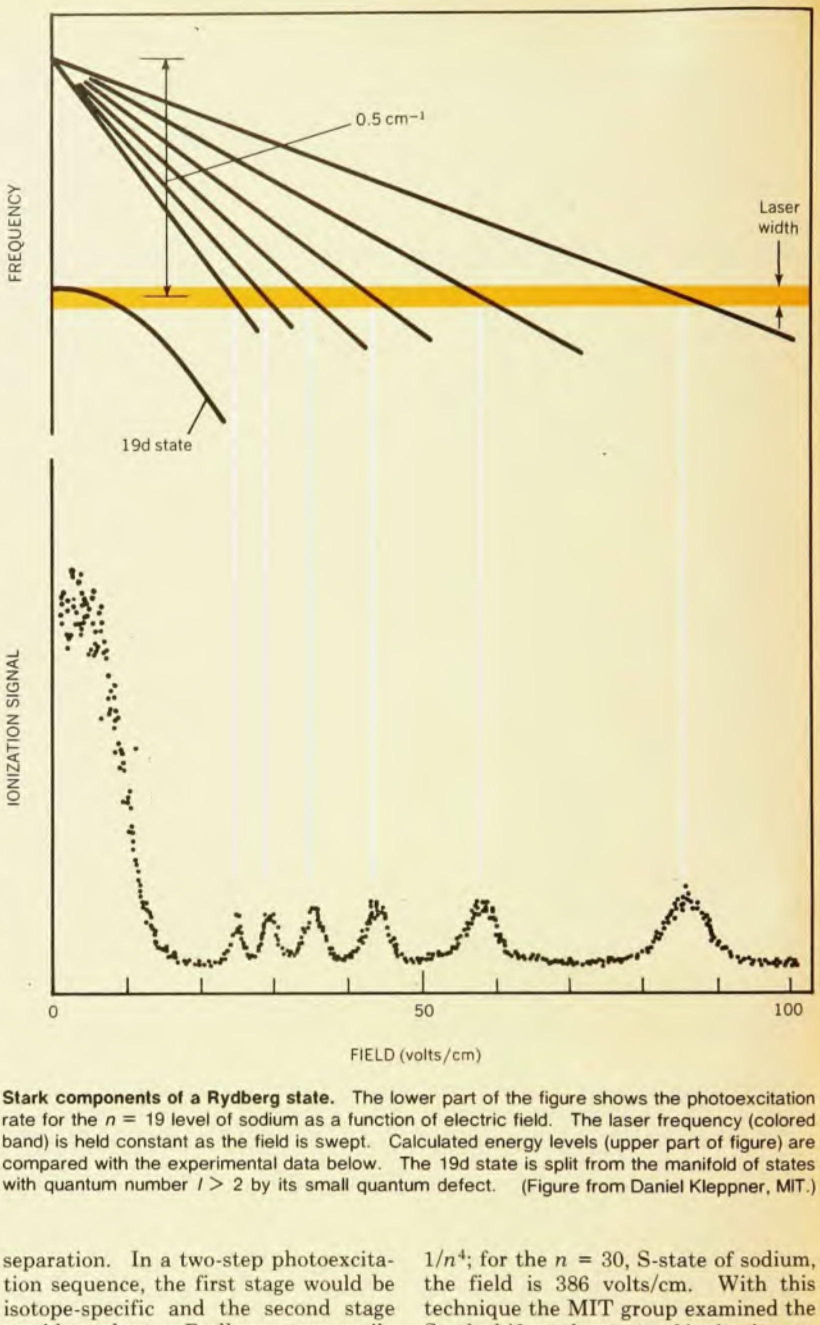
In 1967 H. Hotop and A. Niehaus (University of Freiburg) reported work on collisions between highly excited atoms and ground-state molecules in which the atom is ionized by energy transferred in the (thermal) collision. And at Argonne in 1969, W. A. Chupka and Joseph Berkowitz became involved with high Rydberg states when studying photoionization in the ion source of a mass spectrometer.

With the availability of tunable dye lasers came the ability to pump high Rydberg states one at a time with great precision; hence the recent growth of interest exhibited at the Seattle meeting. Rydberg states are produced at both Stanford Research Institute and the Massachusetts Institute of Technology by two-step laser excitation, whereas at Rice University one stage of electron excitation is followed by a single stage of photoexcitation.

SRI. The work on high Rydberg states at SRI was reported to the Seattle meeting by Thomas Gallagher, Stephen Edelstein and Robert Hill. They use two dye lasers pumped by a single nitrogen laser to excite sodium atoms; first from the 3s ground state to the 3p state, then, (after a 4-nanosec delay of the second laser pulse) from the 3p level to high-lying s and d states in any level from $n = 5$ on up. Detection of the Rydberg atoms in this series of experiments was accomplished by monitoring of the fluorescence from the upper s or d state back to the 3p state. The lifetimes of the higher s and d states were found to follow $n^{2.83}$ and $n^{3.00}$ power laws respectively.

More interesting, however, was the observed variation of the lifetime as other gases were added to the sodium in the experimental region. Addition of helium, argon and neon was found to *lengthen* the lifetimes of the high Rydberg states, not shorten them as might be expected from experience with quenching. The proposed explanation is that collisions between the sodium Rydberg atoms and the added gas atoms result in collisional mixing of the sodium atom in angular momentum states with $l = 2$ or more. The observed lifetime is then the statistically averaged lifetime of all states for which l is not less than 2 and increases as $n^{4.43}$. In the range of n from 5 to 10, the cross section for this process increases as n^4, as does the geometrical cross section of the excited sodium atom.

An exciting possibility, being examined at SRI, is that Rydberg atoms could be used for laser-induced isotope separation. In a two-step photoexcitation sequence, the first stage would be isotope-specific and the second stage would produce a Rydberg atom easily ionized by a relatively low electric field. Yield is expected to be high because the two laser beams are pumping bound, not ionizing, states; the final field-ionization stage is practically 100% efficient.



Stark components of a Rydberg state. The lower part of the figure shows the photoexcitation rate for the $n = 19$ level of sodium as a function of electric field. The laser frequency (colored band) is held constant as the field is swept. Calculated energy levels (upper part of figure) are compared with the experimental data below. The 19d state is split from the manifold of states with quantum number $l > 2$ by its small quantum defect. (Figure from Daniel Kleppner, MIT.)

At MIT, Richard Freeman, Theodore Ducas, Michael Littman and Daniel Kleppner are also working with sodium atoms excited to high Rydberg states ($n = 20$–50) with two-step laser excitation. They differ from the SRI procedure, however, in using an atomic beam and in detecting by field ionization. Each sublevel of a given term ionizes at its own characteristic field value. The scale for the over-all pattern varies as $1/n^4$; for the $n = 30$, S-state of sodium, the field is 386 volts/cm. With this technique the MIT group examined the Stark shift at the onset of ionization, an interesting phenomenon because it represents the extreme case of distortion of a free atom by an electric field.

Kleppner pointed out to PHYSICS TODAY that it should be possible to devise a detector based on transitions in high Rydberg states that would allow photon counting in the infrared and millimeter range. One application could be as a diagnostic tool to examine radiation from tokamaks and other plasma-fusion devices. He also outlined a scheme for using these high n transitions for a determination of the Rydberg in frequency units with an eventual accuracy that could reach 1 in 10^{11}. By providing a frequency calibration for the hydrogen spectrum, the measurement would in effect serve to create an optical frequency standard. An improved value of the Rydberg would also yield a better value of the electron–proton mass ratio.

The work at Rice University is motivated, appropriately enough for a department of space physics and astronomy, by an interest in transitions such as the anomalous recombination lines seen in the radiofrequency spectra of HII regions. These lines arise from high Rydberg states of hydrogen with values of n up to one or two hundred. Colin Latimer, Phil West, Thomas Cook, Barry Dunning and Ronald Stebbings reported to the Seattle meeting their work with xenon atoms in high Rydberg states (n now up to about 40) in collision with SF_6 molecules, which Stebbings says is a relatively easy system suitable for tuning up their experimental techniques in preparation for an eventual attack on the astronomically more important collisions of hydrogen Rydberg atoms.

The Rice group excite Rydberg states in a two-step process, but unlike SRI and MIT, their method is to excite first to the metastable ^3P level of Xe by electron collision, and follow this up with laser photoexcitation to selected pure Rydberg states. Detection is by field ionization, for the lifetime studies: absolute cross sections for ionization of Rydberg atoms in collisions with various targets are now being determined.

At Yale University several years ago James Bayfield's group had extended the earlier work at Culham while studying electron-transfer collisions of protons with hydrogen atoms. The fast neutral beam, prepared by passing a fast ion beam through an atomic-hydrogen target, contained highly excited atoms that arose in the neutralizing collisions. The yield of atoms in state n varies as n^{-3}. A subsequent experiment that used this neutralization as a source of atoms for a merged-beam study of collision processes below 10 eV initially yielded anomalous results; these led to the experimental discovery reported in a February issue of *Physical Review Letters* that low-energy cross sections for Rydberg atoms do scale geometrically as n^4. The Yale group also reported in 1974 on microwave and rf field-ionization studies of these weakly bound Rydberg states with their unique fast-beam method. Koch, Larry Gardner and Bayfield reported more recent studies of this for n between 30 and 56 at the Seattle meeting and at the September Gatlinburg International Beam-Foil Spectroscopy Conference, the latter work using fast laser-pumped Rydberg atoms. One research objective is to determine strong field multiphoton ionization cross sections, which are usually studied with high-power pulsed lasers and ground-state atoms. According to existing theory, many aspects of the problem of a normal atom in a strong optical field of strength, say, 10^8 volt/cm, can be closely matched for hydrogen with n about 50 by a microwave field of 10^2 volt/cm. As Bayfield says, "much of the physics of strong laser interaction with gases can be studied under the controlled conditions of highly excited atomic beams passing through a microwave cavity or waveguide."

Theories of Rydberg atoms and their collision processes are still rather scattered, but the work that has been done is beginning to yield promising results. Michio Matsuzawa of the University of Electro-Communications in Tokyo uses a model in which the highly excited and loosely bound electron behaves nearly as if it were free and slow, although it is nevertheless characterized by a momentum distribution. His report to the Seattle meeting showed how he has improved on his earlier work (with a planewave approximation for the relative motion in the final channel) by using the Coulomb wave function for relative motion in the final channel. With this model he has calculated cross sections for reactions of the type

$$A^{**}(n,l) + B \rightarrow A^+ + B^-$$

(where the double asterisk indicates high excitation) to obtain qualitative agreement with experimental results such as those of Hotop and Niehaus, and Chupka and Berkowitz. Stebbings pointed out to PHYSICS TODAY that Matsuzawa's predictions have been "well borne out" by the absolute Xe–SF_6 data at Rice.

Ray Flannery (Georgia Tech) developed in 1970–73 semiquantal theoretical descriptions of A–B(n) collisions between a neutral atom A or molecule and an atom B in a highly excited Rydberg state n, relevant to radiofrequency observations of HI regions of hot stars. His approach assumes that ionization of B(n) occurs via an *elastic* binary collision, treated quantally, between A and the highly excited, loosely bound electron which is moving with a quantal velocity distribution generated by its parent core A^+. Simultaneous transitions in A can also occur when the binary encounter is *inelastic*, thereby permitting the study of many interesting resonant energy-transfer processes between A and B(n). More recently, in Seattle, Flannery proposed a full quantal treatment of the excitation, de-excitation and ionization of B(n) by collision, not only with neutrals but also with electrons and ions.

Derek Banks, Clive Gee and Ian Percival (all of Queen Mary College, London) and Derek Richards (The Open University, UK) and their collaborators started investigating charged-particle collisions with highly excited atoms because of applications to recombination in astrophysics and laboratory plasmas. They started in 1964 with classical-trajectory methods like those of molecular dynamics, to obtain ionization and charge-transfer cross sections, the latter being in reasonable agreement with the experiments of Bayfield and Koch. More recently they used a variety of classical, semiclassical and quantal methods to obtain excitation cross sections for incident energies between $(50/n^2)$ eV and 10^5 eV. The key to their methods lies with Heisenberg's 1924 form of the old Bohr correspondence principle, which equates quantal matrix elements and Fourier components of classical motion, with errors of no more than about $(100/n)$ per cent. Comparison of this and other theories suggests that resultant errors in cross sections of no more than 6 per cent need be made, with a variety of approximations within well defined ranges of validity. However, outside its range of validity, the binary-encounter approximation, for example, can be out by about two orders of magnitude. —JTS

Young stars

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Meloy of the Princeton University Observatory.[2] The bubble theory also explains, as recently reported by David Hollenbach and McCray,[3] the presence of hydrogen molecules with total angular momentum J greater than about 4, in agreement with observations of OB stars such as Zeta Ophiuchi. Furthermore, photographs of loop structures that might, McCray suggests, be the visible aspects of such wind-driven circumstellar shells have been reported by Peter Brand and William Zealey of the University of Edinburgh in a paper provocatively titled "Cloud structure in the galactic plane: a cosmic bubble bath?"[4]

An alternative theory was published last year by Donald Cox and Barham Smith of the University of Wisconsin (Madison), in which the interstellar medium is seen as being permeated by a mesh of interconnected tunnels containing hot gas of very low density.[5] These tunnels are said to have formed by the interaction of bubble-like supernova remnants, which have lifetimes of about four million years and remain hot during this entire time. When a younger supernova remnant encounters an older one it reheats it, saving it from destruction. This process continues so that roughly half of interstellar space is estimated to be now filled with the resulting tunnel network. This theory yields an approximately correct value for the soft x-ray background and explains the approximate intensities of