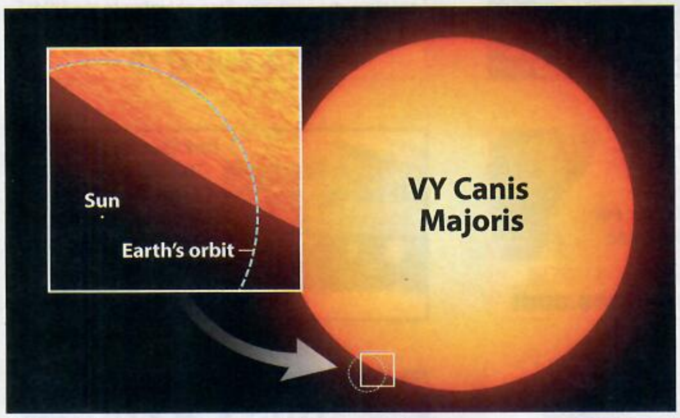
ASK**ASTRO**

Astronomy's experts from around the globe answer your cosmic questions.



VY Canis Majoris, a red supergiant, has a radius that measures more than 1,400 times that of the Sun. OONA RÄISÄNEN

BIG STARS

Q: WHAT IS THE MAXIMUM THEORETICAL SIZE OF ANY STAR BEFORE IT VIOLATES THE LAWS OF PHYSICS?

***James Boyton,** Shreveport, Louisiana*

A: The size of a star is a natural consequence of the balance between the inward pull of gravity and the outward pressure of radiation produced inside the star. When these two forces are balanced, the outer layers of the star are stable and said to be in hydrostatic equilibrium. In general, both the gravitational force and the energy generation rate are determined by the mass of a star. During most of their lives, stars burn hydrogen in their cores, and their structures are almost completely determined by their masses. Later in their lifetimes, energy is generated in a shell surrounding their cores, and the outer layers expand, such as in the red supergiant (for higher-mass stars) and red giant (for lower-mass stars) phases.

Although stars do not have surfaces, the most common definition for the outer boundary of a star is the photosphere, or the location where light leaves the star. The biggest stars are red supergiants, and the biggest has a radius that is approximately 1,800 times the radius of the Sun (432,300 miles [695,700 km]). The reason for this maximum observed size not well understood.

One might guess that a more massive star would grow to be bigger in its red supergiant phase, but more massive stars do not evolve through a red supergiant phase, and they consequently do not grow as large. Perhaps one could imagine a star with arbitrarily large mass and thus arbitrarily large size, but no stars have been found with masses beyond approximately 200 to 300 solar masses — even at that mass, they are smaller than the biggest red supergiants. One of the largest known stars is the red supergiant VY Canis Majoris, which would envelop Jupiter if it were placed at the Sun's location.

Donald Figer
Director of Center for Detectors and
Professor of Imaging Science,
Rochester Institute of Technology,
Rochester, New York

Q: WHAT IS METALLIC HYDROGEN, AND DOES IT EXIST AT THE CORE OF ALL THE GAS GIANTS IN OUR SOLAR SYSTEM?

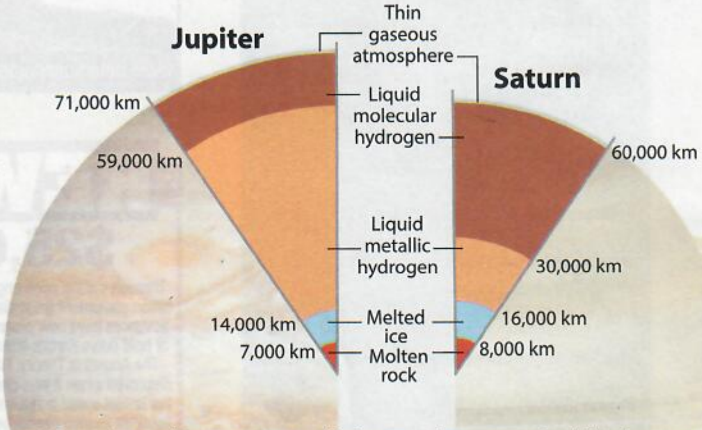
Doug Kaupa
Council Bluffs, Iowa

A: On Earth, elements exist in one of three states: solid, liquid, or gas. The form an element takes depends on its pressure and temperature. While hydrogen is typically a gas on Earth, it can be artificially compressed and cooled to become a liquid or a solid. Even in these states, hydrogen remains a *non-metal* — its atoms hold on to their electrons tightly, so hydrogen conducts heat and electricity poorly. By contrast, metals conduct electricity and heat well because of the arrangement of their atoms, which create a lattice that allows the outermost electrons from one atom to easily transfer to another.

Our solar system has two gas giants: Jupiter and Saturn. Both planets contain a significant percentage of hydrogen, based on their densities. But at the temperatures and pressures deep inside these giants, their hydrogen becomes so heated and compressed that it enters several strange states, including liquid metallic hydrogen.

As I mentioned earlier, hydrogen is a non-metal. But inside Jupiter and Saturn, hydrogen atoms at high temperatures and pressures actually lose their electrons, creating a free-floating stew of hydrogen nuclei (protons) and electrons. Because the electrons are unbound, they can move easily between the nuclei — a property associated with metals. This is metallic hydrogen: hydrogen that behaves like a metal. Metallic hydrogen is conductive, and it's believed to be largely responsible for the dynamo that powers Jupiter's and Saturn's magnetic fields. (Whereas on Earth, that dynamo is powered by liquid iron, an actual metal.)

Uranus and Neptune — our solar system's ice giants — are too dense for hydrogen to be a major component of their makeup. Planetary scientists estimate that hydrogen makes up only about 15 percent of their masses, and furthermore assume that the interiors of these two planets are roughly the same because their masses are so similar. While hydrogen does exist in the ice giants' atmospheres, and is also believed to form a liquid molecular shell deeper down, the hydrogen inside Uranus



Inside Jupiter and Saturn, gaseous hydrogen gives way to liquid hydrogen and, deeper down, liquid metallic hydrogen. The temperatures and pressures inside these gas giants cause hydrogen to take on properties more befitting a metal. *ASTRONOMY*: ROEN KELLY, AFTER KENNETH R. LANG, TUFTS UNIVERSITY and Neptune is never subjected to the temperatures and pressures required to reach a metallic state.

Alison Klesman
Associate Editor

Q: WHAT PRODUCES THE RADIO WAVES FROM A PULSAR, AND WHY DO THEY FORM BEAMS?

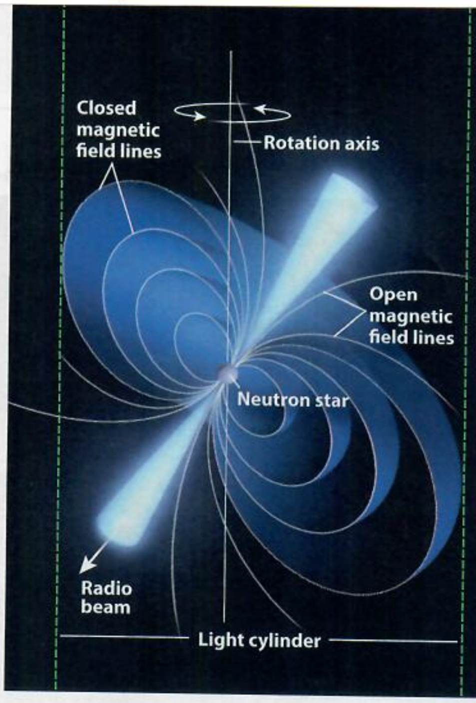
Fr. Taylor Reynolds
Rome, Italy

A: Pulsars are rapidly rotating, highly magnetic compact stars. The rotating magnetic field of a pulsar acts as a generator, accelerating energetic charged particles that then stream along the field lines. A pulsar's magnetic field is like that of a typical bar magnet, emanating from one pole and returning to the other, with an important exception: To keep up with the rotation of the star, magnetic field lines that extend to a sufficiently large distance would need to move at the speed of light, which is impossible. The limit at which the field lines can no longer rotate fast enough is called the pulsar's "light cylinder." Field lines that extend beyond this limit remain "open" rather than returning to the star, as illustrated in the image to the upper right.

Particles accelerated by the pulsar stream along these open field lines and produce radiation that stimulates a cascade of additional particles, which radiate as well. Because the particles are moving relativistically (close to the speed of light), their radiation is beamed in the direction of their motion. The bulk of a pulsar's radio emission is produced at some particular height above the magnetic pole and confined to a narrow beam defined by the field line orientation at that height (which points largely upward). As the star rotates, if this beam crosses the path of the observer, it is seen as a radio pulse. The cross-section of the beam can be complicated, meaning that the pulse shape can depend on which part of the beam crosses the observer's line of sight.

The exact details of where in the open-field region the particles create this radio emission is still under investigation. While many models suggest it is formed close to the poles, recent studies indicate that the emission may occur closer to the edges of the light cylinder. Further studies are ongoing to better understand the details of the process, particularly at higher energies.

Pat Slane
Senior Astrophysicist, Smithsonian Astrophysical Observatory and Lecturer, Department of Astronomy, Harvard University, Cambridge, Massachusetts



Pulsars emit cones of bright radio emission from their magnetic poles as they rotate rapidly. Because these stellar remnants can spin so quickly, their outermost magnetic field lines cannot move fast enough and do not reconnect. ESA/ATG MEDIALAB

Q: I HAVE A PROBLEM VISUALIZING THE COSMOLOGICAL "DARK AGES." WHY WAS EVERYTHING DARK?

John Pratt
New Haven, Vermont

A: The universe has been dominated by starlight for the past 13 billion years or so — most of its history. But for the first few hundred million years after the Big Bang, there were no stars yet. These were the "cosmic dark ages," when the universe appeared featureless and had no recognizable structures. The evocative "dark age" metaphor is a bit misleading, though.

During the dark ages, there was a background of infrared radiation: the remnant glow of the primordial fireball that would eventually, in our present-day universe, cool down into the low-energy photons of the famous cosmic microwave background. In a way, the dark age terminology assumes the viewpoint of a hypothetical human observer, with eyes attuned to perceive visible light only. And in this specific sense, the dark ages really were "dark," meaning the absence of any sources of visible light.

The other important principle at play here is the expansion of the universe, discovered by Edwin Hubble. All light traveling through this "Hubble flow," the generalized movement of galaxies away from any observer, is redshifted because the expansion of space itself stretches the wavelengths of photons, making them redder and less energetic. This is also the fate of the exceedingly hot radiation produced in the Big Bang. At first, the universe was so hot that all hydrogen was ionized, stripped of its electrons by energetic photons. Over time, this radiation became less energetic and "colder."

About 400,000 years after the Big Bang, the photons of this primordial background radiation were already redshifted into the infrared. Their energy was no longer sufficient to ionize hydrogen, so that protons and electrons could combine to form neutral hydrogen atoms for the first time in cosmic history. This moment of "recombination" marks the beginning of the dark ages. To end them, the first stars had to form, the so-called Population III stars. Once they appeared, we again had sources of visible light, and also of higher-energy ultraviolet radiation.

This crucial epoch in cosmic history, when the first stars brought about an end to the cosmic dark ages, is currently beyond the capabilities of our most powerful telescopes, such as the Hubble Space Telescope or the Keck telescopes in Hawaii. When the James Webb Space Telescope is launched around 2020, astronomers will be able to push the horizon of what is observable all the way to the end of the dark ages. That will be a remarkable moment of discovery.

Volker Bromm
Professor, Department of Astronomy, University of Texas at Austin

Send us your questions

Send your astronomy questions via email to **askastro@astronomy.com**, or write to Ask Astro, P. O. Box 1612, Waukesha, WI 53187. Be sure to tell us your full name and where you live. Unfortunately, we cannot answer all questions submitted.