Dear Friends,

It has been an eventful year for Cornell Astronomy, with great highs but also one disappointment.

Let’s get the sad news out of the way first. By now many of you know that Cornell was not selected by the National Science Foundation to continue managing the Arecibo Observatory. This concludes our nearly 50 year association with the telescope, beginning with its design by Cornell’s Professor Bill Gordon. While we are disappointed that our stewardship of Arecibo is ending, we also celebrate the great discoveries made at the telescope during the past 50 years. Rest assured that Cornell astronomers will continue to use Arecibo to make great

Dear Friends

Greetings

Summer 2011

The ‘Nature of Time’ remains one of the unsolved mysteries of the universe. Indeed it was in October 1992 that we formed The Friends of Astronomy, and next year we will celebrate our 20th anniversary. Where has all the time gone? I remember our first symposium as though it were yesterday. Nobel Laureate Tony Hewish opened the proceedings with the Thomas Gold Lecture on Pulsars, and Carl Sagan spoke about the Exploration of the Solar System. Dean Don Randel enthusiastically welcomed all 75 Friends and we all had a great time. Through the years we managed to meet at least once per year and we are still going strong.

Halfway into this period Patricia Fernández de Castro appeared on the scene and started the fabulously informative Orion newsletters twice per year. This issue that you are reading is the 20th. You can find them all at <http://www.astro.cornell.edu/people/friends/orionnews.php>.

Joe Burns Honored

Thanks to the Friends

A Century of Observatories at Cornell

Jupiter:

Barbara Asks!

Books in Science and the Universe

Yervant’s Critical Thinking Corner

The collision of a smaller galaxy with Cartwheel Galaxy sent a ripple of energy into space, plowing gas and dust in front of it and a firestorm of new star creation. The bright blue knots are gigantic clusters of newborn stars and immense loops and bubbles blown into space by exploding stars (or supernovae). Image: HST.

Continued p. 4

Continued p. 7

P. Fernández de Castro, Editor
pf46@cornell.edu
Friends of Astronomy
Galaxies:
A Birthday Celebration in
Special Symposium
not WYSIWYG*
Honor of Martha Haynes

*not “what you see is what you get”
discoveries, via a number of large surveys of the radio sky.

Now on to the good news. During the past year, CCAT has made enormous strides, beginning with a strong endorsement by the Astro2010 decadal survey, and the landmark gift by Fred Young last fall. Following the Astro2010 endorsement, the CCAT consortium submitted a proposal to NSF for partial support of its Engineering Design Phase, during which the telescope’s design will be finalized. Within the past month, NSF has awarded a $4M dollar grant to the consortium, with Riccardo Giovanelli of Cornell as Principal Investigator. There have been other reasons to celebrate new and continuing members of the Department. Rachel Bean was promoted to Associate Professor with tenure in February. She was also honored with a Presidential Early Career Award for Scientists and Engineers along with about 85 other young scientists from all disciplines; a photo of the recipients is at <http://grants.nih.gov/grants/policy/pecase_2009/images/P121310CK-0129.jpg> and Rachel is about five feet to the right of the President.

Yervant Terzian was named the Andrew H. and James S. Tisch Distinguished Continued p. 7
The Cassini spacecraft, in orbit about the planet Saturn since July 1, 2004, continues in excellent health with all twelve of its instruments operating normally. While its extended stay in orbit has allowed observations to be taken with different lighting and seasonal conditions, the years in orbit mean that we can learn more about the evolution in time of features in this dynamic system.

Six faculty, as many senior research associates, and many graduate and undergraduate students in the Space Sciences Building have been involved in planning Cassini’s observations and interpreting some of their results. Here are some of their remarkable findings.

**Highlights in the Rings.**

Saturn’s dazzling rings are composed of innumerable chunks of nearly pure water ice that range in size from marbles to school buses. The washer-shaped disk that orbits Saturn is surprisingly thin, merely 10 m thick, although the ring system is some 275,000 km wide. Ever-changing, the rings provide scientists with a readily accessible model for other astrophysical disks such as galaxies and the protoplanetary nebula out of which our solar system formed.

Moons produce much of the understood structure in the rings. Both Pan and Daphnis (discovered in Voyager and Cassini images, respectively) open narrow gaps in the rings. Other moons that lie a little ways outside the rings gravitationally drive waves that strongly distort the ring’s fabric as well.

Matt Tiscareno, a senior research associate at Cornell, and colleagues have detected relatively large (~ 1 km) moonlets embedded within this disk that are called “propellers” after the shape of the disturbance that they create in the ring around them. After following a dozen of these moonlets for years, they have learned that their orbits are evolving in ways that may mimic the orbital evolution of planets during the early history of the solar system. Matt is now devising mechanisms that might explain these motions; other scientists internationally are coming up with competing ideas. Matt has published his results on this exciting topic in a series of papers in Nature, the Astronomical Journal and the Astrophysical Journal Letters.

Matt Hedman, another senior research associate here, and collaborators have noticed a strikingly regular pattern of bright and dark bands that stretches across the inner ~20,000 km of the ring system. They suggest that the ring is corrugated like a tin roof so that the translucent ring’s brightness depends on the path-length through which light passes. Because the spacing between the bands varies systematically with distance from the planet (being tighter close to the planet), Matt argues that this pattern is being progressively twisted up by the planet’s gravitational attraction after starting as a flat but slightly inclined disk in 1983. Cassini has actually witnessed this “winding up” over the last few years, validating the model. The initial tilting, Matt suggests, occurred when a cometary cloud impacted a broad swath of the rings in 1983. Mark Showalter, Ph.D. ’85, and colleagues have detected similar features in Jupiter’s ring that may be a “smoking gun” for this sort of process. He thinks that, just as Matt has argued for Saturn, the corrugation pattern in the Jovian system can be traced back to an event in 1994, about the time that comet Shoemaker-Levy 9 crashed into Jupiter. These two papers appeared in the May 6, 2011, issue of Science.


**Cassini Continues Circling Saturn**

(continue)

**Enigmatic Enceladus.**

Spectacular geysers of water vapor and ice crystals have been noticed shooting from fissures near the south pole of this 500 km-wide moon. Senior research associate Paul Helfenstein is leading a group of geologists who study this bizarre region. Since the surface temperatures hover at -200º C, the water must come from a warmer region; for example, a liquid ocean might exist deep beneath Enceladus’ surface. By flying several times only tens of km above the satellite and through these plumes, Cassini has sensed its chemical make-up, which is dominated by water and includes carbon dioxide, methane and other organic molecules. With liquid water potentially accessible, an energy source that drives the system and organic (carbon-rich) surface materials available, Enceladus has—to everyone’s surprise—become a site of strong astrobiological interest.

**Titan.**

Following Voyager observations thirty years ago, Saturn’s largest moon, Titan, was suspected of possibly having a weather system as active and complex as Earth’s, but involving methane and/or ethane, rather than water, as condensable molecules. Jonathan Lunine, who will be joining our faculty as the David Duncan Professor, has been a leader in these studies. At Titan’s frigid temperatures and high atmospheric pressures, these hydrocarbons can be liquid, gas or solid. Now the evidence for liquids on the surface is overwhelming.

Cassini cameras have tracked methane clouds as they form and move across the satellite’s face, both near the equator and at the poles. Following the passage of such weather systems, surface regions become darkened, much as a violent summer thunderstorm might wet a Southwestern desert.

Apparent lakes have been spotted in radar, infrared and visual images. These exhibit shoreline features (e.g., smooth shorelines but also deltas at the mouths of apparent river valleys). From radar and spectroscopy, these “lakes” are known to have flat surfaces and to contain methane or ethane. Jason Soderblom, a research associate here, has investigated the glints of sunlight that have been noted to reflect from a polar lake’s surface. Most recently we have even seen that the shorelines of the “lakes” expand and contract over time, presumably as the lakes fill with liquid that eventually evaporates.

According to its original mission plan, Cassini was to observe the Saturn system for four years (2004-2008), but its mission was extended until 2010 to monitor the planet and rings through the Saturnian equinox (when the Sun passes through the ring plane). Last year NASA approved continuing the mission through 2017, assuming that fuel supplies last and the spacecraft remains healthy. This will allow Cassini, with its superior instrument set, to scrutinize the Saturn system through solstice, completing one half-cycle of Saturn’s seasons. Then this most productive spacecraft will go out in grand style: engineers plan to smash Cassini into the planet at nearly 35 km/sec after performing twenty orbits that will repeatedly pass through a 6000 km-wide gap between the ring system and the planet itself.

-Joseph Burns
Dear Friends  
(cont.)

University Professor at the Trustees’ meeting in May. This is one of a small number of extremely prestigious University professorships at Cornell. It is a singular honor for one of Cornell’s greatest professors.

Jonathan Lunine will join our Department in July as the David C. Duncan Professor in the Physical Sciences. Jonathan is one of the pre-eminent planetary scientists in the world, an expert on planets both within the solar system and orbiting other stars. We are extremely excited that he will become our colleague.

The Department also conducted a search for a new assistant professor this past year, and as I write this we are close to concluding that search. I will update you on the outcome in the next edition of the Orion.

And we are not stopping our march to the future there: the College of Arts and Sciences has authorized our Department to conduct another faculty search next year. We look forward to hiring an assistant professor working on scientific issues related to CCAT—which includes just about everything in the Universe. These are exciting times for our Department!

-Ira

Joe Burns Honored

As we were closing this issue we learned that Prof. Joe Burns was awarded an honorary Doctor of Science degree from his alma mater, the Webb Institute on June 18, 2011. Webb Institute is a small and prestigious engineering college in Glen Cove, N. Y. Founded in 1889, it specializes in naval architecture and marine engineering.

Congratulations, Joe!

Thanks to the Friends!

It’s been a busy semester and we are happy to thank you for making some of that work possible.

On November 9, 2010, Alex Wolszczan (Penn State) presented the Charles and Barbara Burger Special Colloquium. Alex presented a talk on “Second Chance Planets,” about planets around neutron (dead) stars. On February 16, 2011, astrophysicist and cosmologist John Mather (NASA/Goddard Space Flight Center), 2006 Nobel Prize in Physics, delivered the inaugural Yervant Terzian Lecture. His talk, which took place in Schwartz Auditorium, was entitled “From the Big Bang to the Nobel Prize and on to James Webb Space Telescope and the Discovery of Alien Life.” The following day he gave an Astronomy Colloquium on “The James Webb Space Telescope: Science Opportunities and Mission Progress.” Doug Hamilton (University of Maryland) presented the Josephine Lawrence Hopkins Foundation Colloquium on “The Orbital History of Jupiter’s Galilean Satellites” on March 3, 2011. Finally, Jerry Sellwood of Rutgers University presented the Maryanne Shelley Jessup MacConochie Colloquium on “New Developments in Spiral Structure Theory” on March 10, 2011.

This year’s Terzian Scholarships, which were a gift from the Friends on Yervant’s 60th birthday, were awarded to two Astronomy majors, junior Melissa Halford ’12 and senior Samuel Johnson Stoever ’11. Melissa is part of Hubble Fellow Kevin Covey’s team, which is researching low mass stars. Sam, who is also a theoretical mathematics minor, worked with the Infrared Spectrograph Science Center during his junior and senior years.

François Foucart received the 2011 Cranson W. and Edna B. Shelley Award for Graduate Research in Astronomy in recognition of his research in simulations of black holes and neutron stars, as well as for his work on disks around stars. Melissa Rice was awarded the 2011 Cranson W. and Edna B. Shelley Outstanding Teaching Assistant Award for her outstanding talent and commitment to undergraduate education, both as a TA in several of the Department’s writing courses and as the instructor of this year’s freshman writing seminar, Astro 1109, Exploration of Mars. Bryant Garcia and David Kotfis shared the 2011 Cranson W. and Edna B. Shelley Award for Undergraduate Research in Astronomy for their outstanding research accomplishments involving simulations of black holes and neutron stars.

Andrew Bass ‘12 is the summer 2011 Josephine Hopkins Fellow. Andy is searching for transient sources, a type of neutron star, in the Very Large Array archive.

The Department is very grateful to the Friends for their support. Thanks!

Greetings  
(cont.)

We owe deep gratitude to Robert A. Cowie’56, who has been Chairman of the Friends group since the beginning. There have never been any dues for membership, but the Department and the University are grateful to the many contributions that the Friends have made through the years.

The Department looks forward to planning our 20th anniversary Special Symposium for the Friends of Astronomy and to seeing many of you then!

-Yervant Terzian
Andrew H. and James S. Tisch
Distinguished University Professor

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-Yervant Terzian
Andrew H. and James S. Tisch
Distinguished University Professor
Cornell’s astronomers are renowned for pushing the limits with revolutionary telescopes on airplanes and in space, and for developing clever instrumentation for large telescopes on the ground. But astronomy at Cornell started in Ithaca, with modest telescopes that made discoveries of their own—and which, today are an essential part of every undergraduate astronomer’s education. One man played a core role in the early days of this adventure, just as another would see it through to completion.

Samuel Latimer Boothroyd came to astronomy by the odd entry of irrigation engineering. He arrived for his first tour at Cornell in 1904 as an instructor of civil engineering, rising to assistant professor of geodesy and topographical engineering in 1908, while also serving as Cornell’s official surveyor. After a spell in Seattle as associate professor of mathematics and astronomy, he returned to Cornell in 1921 as a full professor of astronomy and geodesy in the school of civil engineering.

It was in this capacity that Boothroyd led the building of the second Fuertes Observatory (named after Cornell civil engineering professor Estevan Fuertes, 1838-1903) in 1916. When the facility was completed the following summer, he installed “transit” telescopes to perform geodesic work, but shortly he commissioned a proper astronomical telescope. Installed in late 1922, it was dedicated the following year as the Irving Porter Church memorial telescope.

Boothroyd quickly began to push technological limits with it. In January 1925, the narrow shadow of a total eclipse of the Sun passed directly over Ithaca. A team of astronomers from Lowell Observatory in Flagstaff, Arizona made the cross-continental journey to bring instruments to image the Sun. To record the fingerprint of the last glimpse of light from the Sun’s edge as the moon covered it, Boothroyd crafted a new instrument, a spectrograph, just in time for the eclipse. Although a combination of extreme cold and missed communications thwarted his effort, successful images of the eclipsed Sun were recorded, and a tradition of collaboration with Lowell Observatory was established.

Now fully engaged in astronomy, Boothroyd spearheaded the creation of the new Department of Astronomy in 1932. A year earlier, in 1931, he had begun constructing new astronomical instruments using reflective mirror elements coated, for the first time, with evaporated metal films, instead of chemically deposited silver. He wanted to push observations into the ultraviolet, at least as far as the atmosphere allows. Silver coatings (and certain glass lenses) absorb ultraviolet radiation, so innovation was necessary to reach these unexplored domains. Boothroyd provided it. The rapidly tarnishing silver-coated mirrors were relegated to obscurity and this Cornell invention quickly became the standard for all astronomical telescopes.

In 1933, Boothroyd took some of his new ultraviolet-optimized devices to Lowell Observatory, and used them at telescopes located at Mars Hill (7,500 ft elevation) in Flagstaff, and then as high as 10,500 feet at a small station maintained by Lowell on San Francisco Peak, north of the city. The goal was to see if more ultraviolet radiation would reach high mountaintops, though the bulk of ultraviolet is scoured by the ozone layer, much higher in the atmosphere.

By this time, Boothroyd had gained a new assistant, R. William Shaw, who carried out his instrumental designs and contributed some of his own. Together, they planned a larger but lightweight telescope that could be carried high into the mountains and erected to pursue even fainter targets further into the ultraviolet spectrum. Shaw became a

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1 The science of measuring star positions to determine the shape of the Earth—and where one is located upon it.
visiting professor during the summers at Arizona State College, continuing the Arizona partnership, and together they gathered components for a novel, magnesium-framed telescope tube.

A new opportunity for instrumental experimentation arose in 1932. Corning Glass had received the technologically challenging job of casting a gigantic mirror blank for the planned massive Palomar 200” telescope in California. Corning prepared a large quantity of the new Pyrex glass and poured two 25” test mirror blanks to come to terms with this new material. Both were polished and figured, and Boothroyd secured one for the University.

Unfortunately, war intervened and all nonessential engineering activities in the country ended. Boothroyd retired in 1942 at the age of 68. His assistant, Shaw rose to departmental chair but did not pursue Boothroyd’s ultraviolet ambitions. The telescope sat in storage, awaiting a new mission and champion.

James R. Houck arrived at Cornell in 1962 as a graduate student, earning his Ph.D. in 1967 under Professor Ray Bowers. After a postdoctoral position at the Naval Research Laboratory under Cornell Professor Martin Harwit, who was taking a sabbatical research year, he returned to Cornell as an assistant professor in 1969.

In contrast to Boothroyd, Houck wanted to build new detectors to explore not the ultraviolet, but the other side of the spectrum next to visible light, the infrared.

The atmosphere itself blocks most infrared light outside a few narrow windows, just as it blocks ultraviolet beyond a short wavelength cutoff. Houck was working on small telescopes and detectors to operate onboard high-flying aircraft and on quick flights on military sounding rockets high above the atmosphere. But it was essential to test these new devices before sending them up on expensive flights. The Fuertes Telescope, by now a historical artifact,
would not suffice: the lenses blocked infrared light. He needed a mirror-based telescope, and Cornell had none.

Except it did. A legacy of Boothroyd and Shaw’s work in the 1930s, the Corning blank and tube was waiting to be deployed. Houck partnered with a Cornell undergraduate, George Gull ’72 (Mech E.) who made the design and construction of a telescope mounting the subject of his senior thesis. In 1973, Harwit negotiated a $10,000 donation from M. John Hartung ’08 (Mech. E.), an alumnus who arrived in the College of Engineering as an undergraduate at the same time as Boothroyd joined it as an instructor and, who graduated the year Boothroyd (who had died in 1965) rose to assistant professor.

From this historical legacy, a new facility arose, which would be commissioned the Hartung-Boothroyd Observatory (HBO) in 1975. Boothroyd’s foresight, Hartung’s beneficence, Houck’s vision, and Gull’s industry created a facility for a new generation of students and researchers.

The Hartung-Boothroyd Observatory may not be large in comparison with its brethren, but with modern digital detectors, it can replicate most experiments done with the largest telescopes in the world during the era of photographic film. Each fall, astronomy students undertake a journey in history as they take our Astro 4410 course, Experimental Astronomy. With Boothroyd’s telescope and Houck’s instruments, they measure the mass of distant galaxies, determine the ages of star clusters, and rediscover the sense of wonder that was felt by astronomers who first conducted these classic experiments.

And the telescope is still quite capable of doing new things. Constant upgrades, such as a new generation digital detector contributed by Friends of Astronomy Chuck and Barbara Burger in 2006, keep it at the cutting edge of small observatory capabilities. Students in Experimental Astronomy find new experiments to replicate: one last fall measured the size of a planet orbiting another star. Other courses optionally feature visits to HBO. Students select targets, engage instruments, and soon see direct indications of the composition, temperature, or speed of an object. Summer students learn the basics of spectroscopy. Moreover, several generations of graduate students have tested parts of their new equipment at HBO before committing them to large telescopes. This fall, HBO will support observations to complement those taken by the European Herschel infrared space observatory.

Continued p. 16
Jupiter is the largest planet in our Solar System and, from the perspective of someone living on a terrestrial planet (all of us!), it might be considered very simple. It has no rocks, no oceans, no plate tectonics. It is essentially a ball of gas, with no solid surface. When we look at it, all we see are clouds. Nevertheless, it is actually a complex place with much to teach us and help us understand our own planet. By using the broad diversity we find in the Solar system to test what happens when the fundamental parameters change, scientists develop general theories that apply to Earth as well as to other, vastly different, planets. This, we hope, will lead to an adequately complete understanding of what processes matter for each planet. Another reason why Jupiter is of significant interest is that it may be the best example of the extra-solar planets that are being discovered elsewhere in the galaxy now. If we ever hope to gain a good understanding of those distant bodies, we need to explain what we observe on our own giant planets.

At Cornell, prof. Peter Gierasch, senior scientist Barney Conrath, Atmospheric Sciences graduate student Mike Roman and I have spent many years trying to tease answers from Jupiter about both big picture questions about planets and about some Jupiter-specific details. The questions we are trying to understand range from extremely fundamental to quite arcane. For starters, we don’t even know what the clouds we see on Jupiter are composed of! For that reason, we don’t really know at what level in the atmosphere our cloud-tracking has measured Jupiter’s winds. We don’t know what makes the clouds break up into separate East-West stripes. We don’t understand what causes the smaller storms on Jupiter, let alone what maintains the very large and long-lived Great Red Spot (nor why it is red).

We have a pretty good theoretical understanding of the most fundamental question, what the clouds of Jupiter should be made of. If you take a mixture of gases similar to the sun’s, and cool it down to the temperatures Jupiter experiences at its distance from the sun (110K to ~280K depending on the altitude of the clouds), three different molecules will condense. This is in great contrast with what we see on Earth, where only water forms the clouds we’re so familiar with (especially in Ithaca!). If we were in an aircraft flying higher and higher in Jupiter’s atmosphere, we would encounter three distinct cloud layers. Starting deep in the atmosphere, at pressures 5 times terrestrial sea level pressure (5 bars), we think we’d encounter a water cloud level. It’s interesting to note that, while water clouds are found much deeper in the atmosphere than on Earth, they still occur right near the freezing point of water. Because both phases of water (ice and liquid) are in the water clouds, lightning flashes can happen, and indeed we have observed lightning directly on Jupiter’s night side using the Galileo spacecraft. However, regions with lightning occur in storms significantly stronger than ours, and likely are accompanied by much heavier rainfall or snowfall than we ever see on Earth. From analysis of Galileo images, we know that thunderheads tower some 120km tall (compared to ~10km on Earth), with a horizontal scale of ~1000km (compared to ~10km on Earth)!

Jupiter: our Giant Gas Planet
Senior Research Associate Don Banfield studies the atmospheres of the different bodies in our solar system with data collected on the ground and in space. He also develops powerful data-collecting instruments for spacecraft.
While Galileo’s probe was a washout, we hope to someday send another probe. To settle once and for all the question of what we see when we look at Jupiter (and the questions that follow from that!), we are currently developing an instrument for a descent probe to Jupiter (or Saturn, Titan or any other planet with clouds). This *nephelometer* shines a laser on the cloud particles that it falls (or flies past) and then measures the light that is scattered off of them at various angles, polarizations and wavelengths. We believe that this way we can identify not only the size, number, density and shape of the cloud particles, but also their composition—water, ammonium hydrosulfide or ammonia (or some other exotic material). Compared to instruments that you might use on Earth, our instrument not only must be autonomous, light and rugged for use on a spacecraft. It also has to identify the molecules that form the clouds. With an initial round of NASA funding, we’ve built a lab in the Space Sciences basement and demonstrated the feasibility of the techniques involved in our conceptual nephelometer instrument. We will apply next year to NASA for funds to develop it to the point we could propose it for future missions to any of the planets with clouds. If and when the nephelometer is deployed, we might unlock the mystery of our giant gas planets’ clouds.

-Don Banfield
Q. How do stars form and how do they generate enough heat to shine?
A. Heat is not a problem. In fact, excess heat is an impediment to star formation. To form a star, a gas cloud must rid itself of heat.

Stars form in the collapse of clouds of gas that start out orders of magnitude less dense than a star. They also have considerably more heat content—technically, entropy—than the gas inside a typical star, and they have to get rid of that in order to collapse to very high density. This may sound odd to you, since the temperatures of cold cores of molecular clouds may be about 10 degrees Kelvin, whereas the temperature inside the core of the Sun is about 10 million degrees Kelvin. But the very low density of a molecular cloud core, perhaps a million protons per cubic centimeter, compared with the density at the center of the Sun, which is about 20 powers of ten higher, means that the cloud core is much “hotter” in that its entropy is several orders of magnitude higher. Major coolants are molecules and dust grains embedded in the gas.

Interstellar gas clouds may also have weak magnetic fields. Collapse along the lines of force of the magnetic fields is easier than collapse perpendicular to them. Thus, interstellar clouds must also shed magnetic fields if they are to collapse.

Finally, an interstellar cloud may have significant rotation, which will support it against collapse in directions perpendicular to the rotation axis. For a cloud to collapse in its center, it must transport angular momentum outward, thus leaving the core rotating slowly enough that its rotation does not prevent condensation to higher density.

Once a gas cloud has managed to overcome these impediments it can collapse toward becoming a star. It will still have significant heat content since it doesn’t need to get rid of all of its heat, but just enough to be able to collapse. While its collapse is impeded, the collapse rate is relatively slow, governed by how fast the star can get rid of heat, magnetic fields, and rotation. In other words, the collapse is slow compared with free fall, the rate at which the cloud would condense if it collapsed under its own self gravity with no impediments at all.

Ultimately, the gas cloud can reach a state where rotation and magnetic fields do not matter much, and enough heat has been lost that densities much greater than that of interstellar gas can be attained. If it does, the star will first reach a point where the residual heat provides enough pressure to almost balance gravity. We call this hydrostatic balance.

In hydrostatic balance, the pressure decreases outward from the center of the star, thus supporting the star against gravity, which wants to pull
the star inward. Higher pressure implies higher temperature, so the star is hotter at the center than on its surface—and much hotter than the largely empty space outside. Since heat flows from hot to cold the star must expel energy outward. Most of that heat emerges as radiation, because this is by far the most efficient way to expel energy into the near vacuum outside. That is why stars shine.

As a star shines, it loses energy. Where does the energy come from? There are two sources. One is very slow contraction. In the late stages of the formation of a star this is the main source of luminosity of the star: as the star gets smaller, its energy decreases roughly in proportion to one divided by its radius. The rate of contraction is directly related to the rate of energy loss, and is therefore controlled by the rate of heat flow through the star. The contraction is painfully slow, and a star may take hundreds of thousands of years or longer to collapse by a factor of two in radius.

During this phase of the life of a star, contraction makes the core of the star progressively hotter and denser. Eventually, the core may become hot enough that nuclear reactions become possible. When this happens, the star stops shrinking because it no longer needs to do so to provide the energy that it must lose to radiation because heat must flow outward from its hot core to the cold outside space. In detail, the star first burns Deuterium, a heavy isotope of hydrogen. Since there is comparatively little Deuterium in the Universe, this is a short phase in the life of the star. After it burns up its Deuterium, contraction resumes until the star can burn ordinary Hydrogen, the most abundant element in the Universe.

At this point, contraction halts once again, and the star joins the main sequence. This is by far the longest phase of the life of a star. For the Sun, the main sequence phase will last about 10 billion years.

Once a main sequence star has burned all of the Hydrogen it can, its core begins to contract once again. This is because the relentless flow of heat from hot to cold must be balanced somehow by a loss of energy of the star, and shrinking is the only way this can happen if there is no nuclear burning. As contraction continues, the core heats up and becomes denser. Ultimately, it becomes dense and hot enough to trigger a new round of nuclear reactions, first renewed Hydrogen burning in a shell surrounding the core, then burning of Helium, the product of Hydrogen burning, in the core itself. Somewhat paradoxically, as the core of the star becomes ever denser, the outer regions of the star expand enormously, leading to formation of a red giant star.

This sequence of contraction interrupted by nuclear burning is one of the keys to understanding the evolution of stars. Fundamentally, it arises because a star...
Books in Science and the Universe


*Genius* is a short booklet (96 pages) in magazine format with articles on some of the most famous scientists who have advanced our knowledge of how nature works. Charles Darwin and Albert Einstein are featured in some detail as are Sir Isaac Newton, Richard Feynman, Kurt Godel, Stephen Hawking and Murray Gell-Mann. Others featured are Sir Arthur Eddington and Marie Curie. The contemporary “Genius” generation is represented by Ed Witten (string theory) and Fotini Markopoulou-Kalamara (theoretical physics). The booklet is a collection of impressive biographies accompanied by significant illustrations.


*Quantum Man* is the scientific story of Richard Feynman. Lawrence Krauss follows the timeline of Feynman’s thinking in quantum mechanics from the time he was a graduate student at Princeton to his time in Los Alamos when he worked for the Manhattan Project. Later Krauss describes his years at Cornell and at Caltech. Though the subject is about advanced quantum mechanics thinking, the book does not contain complicated equations. Krauss is able to capture the “agony and defeat” of scientific explanations at the threshold of modern physics.

The Definition of Words and the Heap Paradox

We define a collection of things put together in a place as a “heap.” Suppose that we have a heap of about 100 sugar cubes. Now if I take a sugar cube away, I still have a heap of sugar cubes. If I continue to take away one cube at a time, then I still have a heap left. But clearly when I have a few or two or one cubes left, that is not a heap, yet we started with a heap. Since there is no definition of how many things together make a heap, and since one or two or a few cubes do not make a heap, then we do not know when a heap stops being a heap.

The phenomenon of vagueness is at the heart of this paradox. Vagueness occurs when there are borderline cases, but philosophers debate whether it is a matter of linguistics or whether vagueness may be a property of objects.

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*Barbara*

is (nearly) in balance between the outward force arising from the pressure decrease between its core and outer boundary, and the inward force of its self gravity. This pressure gradient makes the star hottest in its core, and the relentless flow of heat from hot to cold causes it to radiate. Conservation of energy says that the energy lost by the star must be exactly in balance with the energy it radiates. There are only two ways for this to happen: nuclear burning or contraction. Thus, stars are always in a state where one or the other is providing the radiated energy.

- **Barbara Burger** (for the question)
- **Ira Wasserman** (for the answer)