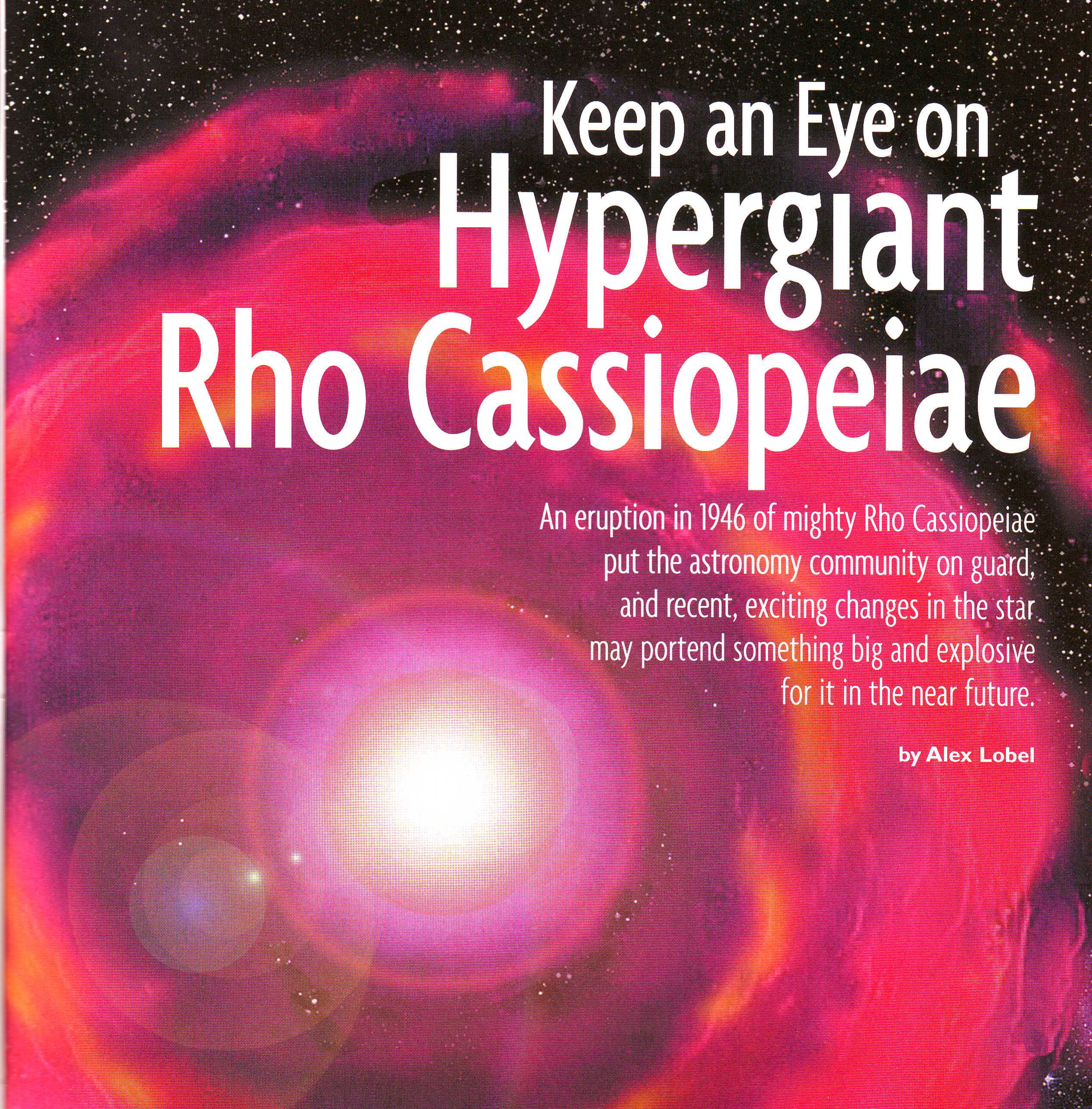
Keep an Eye on Hypergiant Rho Cassiopeiae

An eruption in 1946 of mighty Rho Cassiopeiae put the astronomy community on guard, and recent, exciting changes in the star may portend something big and explosive for it in the near future.

by Alex Lobel



She goes without a proper name, but recently the 17th brightest star of the northern constellation Cassiopeiae is drawing the attention of amateur and professional astronomers worldwide. In the spring of 2000 Rho Cassiopeiae, or ρ Cas, brightened up to magnitude 4.0, then dimmed to an astonishing 5.3 over the next half year, while changing its usual yellowish-white color to the red-orange glare of Betelgeuse (α Orionis). Such a rapid, extraordinary change was also observed for the star in 1946, bringing it to the attention of astronomers everywhere.

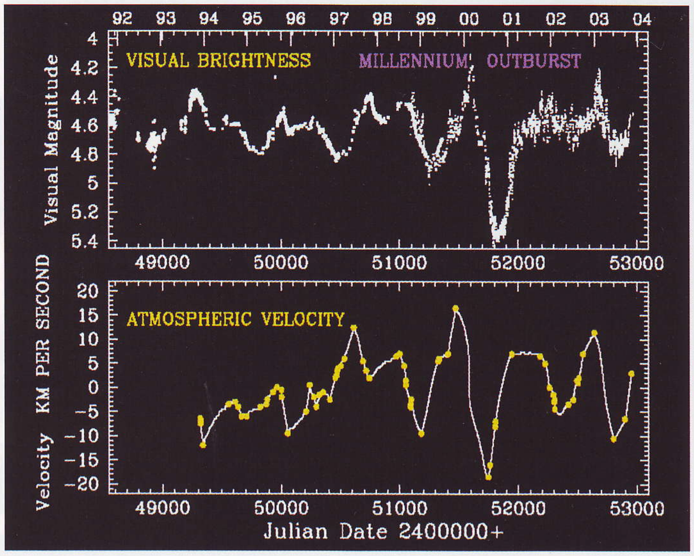
Various types of variable stars are known to change their visual brightness in a rather predictable way—stars such as Mira (o Ceti) and Algol (β Persei). And the R Coronae Borealis stars can suddenly dim by several magnitudes; they are much fainter and less intrinsically luminous than ρ Cas, however.

Indeed, shining at about half a million times the Sun's luminosity, Queen ρ Cas is known to be one of the most luminous cool stars of our Galaxy. Tucked away in the Orion spiral arm of the Galaxy, at an approximate distance of ten thousand light-years, it is possibly the most distant star with a surface temperature comparable to that of our Sun that can easily be observed with the unaided eye.

The study of luminous cool (yellow to red) and hot (blue to white) stars addresses a number of key astrophysical questions that pertain to the very existence of stellar objects in general.

- Why do we observe many more luminous hot stars than luminous cool stars in the Galaxy?
- Why do we not see cool stars more luminous than about a million Suns?
- What physical mechanisms determine the relationship between a star's luminosity and its mass, the most fundamental parameter?
- Are these mechanisms universal in the sense that they always operate regardless of other intrinsic stellar parameters such as radius, surface temperature, composition, age, and rotation, or external properties like binarity, group or association membership, or even the star's location in the Galaxy?

To phrase the last question differently: why do we observe stars with, for instance, comparable surface temperatures and total intrinsic magnitudes, but possessing very different spectral signatures?



Visual brightness variations of ρ Cas observed over the last decade are strongly related to changes in the velocity of the atmosphere, as inferred from the position of absorption lines in the hypergiant's optical spectrum. During the 2000 outburst, the star dimmed by 1.3 magnitudes and the surface temperature decreased by at least 3000 K as a result of the supersonic expansion of the entire atmosphere approximately one hundred days earlier. Yellow points in the figure indicate flow velocities in the lower atmosphere measured from an individual absorption line. Photometric data in upper panel are courtesy of the American (AAVSO), French (AFOEV), and Japanese (VSNET) amateur observer groups. Plot courtesy of the author.

ence (or absence) of dark features called "spectral absorption lines," first cataloged for sunlight by Joseph von Fraunhofer in 1814. These spectral signatures contain a wealth of information about the physical circumstances of the stellar atmospheres in which they form but that cannot be deduced from observing the brightness of a star or its variability over time. The spectrum (Latin for "ghost") of a star contains the unique fingerprints of the chemical elements present and is determined by the physical mechanisms that distribute the energy of photons into various visible colors and those invisible to the human eye—from energetic gamma rays and x rays to lower-energy infrared, microwave, and radio waves.

X rays and radio waves have yet to be detected from ρ Cas, but the

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ρ Cas is a distant star for which modern, space-borne imaging does not reveal clearly discernible structures in its surrounding environment—for example, there appears to be no reflection nebula—and this is real hindrance to our efforts at inferring its stellar properties. But ρ Cas does have one formidable advantage over all other luminous stars: its extraordinary optical brightness.

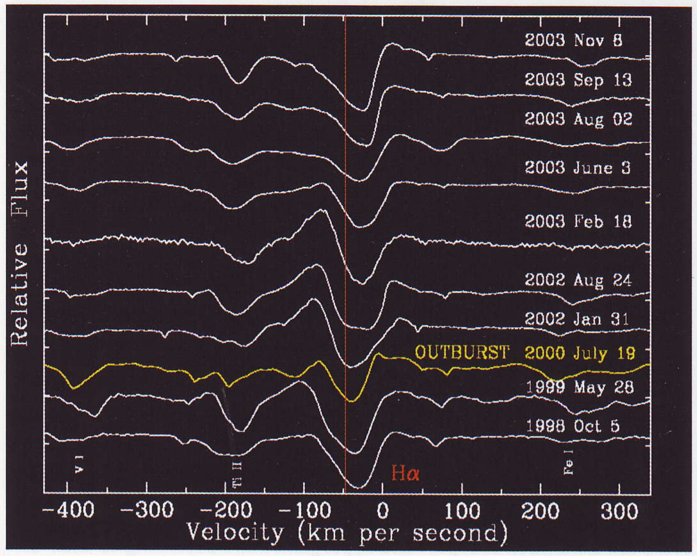
Spilling the Light Fantastic

More than a century ago astronomers noticed that when the light of stars is split into colors, the stars can be classified according the presspectrum of its visible light has been recorded with high precision for more than a century. In particular, we have discovered that ρ Cas is one of very few cool stars for which recurrent spectral changes can be linked with the star's semi-regular brightness changes: the positions of the spectral absorption lines change periodically with time, shifting right to left and back again, while the lines' shapes and darknesses change as well. They are occasionally even brighter than the surrounding, continuous spectrum and become bright "emission lines."

As a doctoral student at Utrecht, the Space Research Organization of The Netherlands, I organized in 1993 a small group of researchers with the goal of combining spectral observations of ρ Cas from two telescopes. Since then, however, the group's efforts have grown to include continuous monitoring programs from six different telescopes in the United States and Europe. One would normally require a large telescope for the ground-based, high-resolution observations we collect from ρ Cas, but the star is so bright in the optical portion of the electromagnetic spectrum that a high-quality and high-resolution spectrum can be collected within an hour using one- to two-meter telescopes. Fortunately, we have access in the northern hemisphere to such telescopes with high-resolution spectrographs, which permits us year-round, spectroscopic access to ρ Cas. Indeed, our observational campaign on this star is one of the largest ground-based, high-resolution, spectral-monitoring programs ever conducted.

But ρ Cas is more than just a cool, luminous star. Unlike many other bright stars in the sky, there is no observational evidence that ρ Cas is part of a binary or multiple-star system. This was suspected before 1993 and has in the meantime been confirmed by our spectral monitoring program. This fact may appear to be only a detail in a much bigger picture, yet for a stellar spectroscopist the difference between binarity or other multiplicity and not is as great as that between day and night. The observed shifts of the spectral lines could be influenced, if not solely produced, by gravitational tugs on large ρ Cas by smaller but sufficiently massive companions. If this were the situation, it would be practically impossible for one to directly correlate the remarkable line shifts with the brightness changes of the star itself, compromising the ultimate goal of our monitoring program to document and unravel the physical cause for this dependence.

In the summer of 2000, after more than six years of continuous spectral monitoring, ρ Cas finally revealed more than we had ever hoped for. The star brightened and then abruptly dimmed by more than a full magnitude—almost three times dimmer—all the while displaying tremendous spectral changes. After more than half a century since its similar, dramatic event in 1946, enigmatic ρ Cas revealed its deepest secrets through a new eruption—likely a once-in-a-career event for an astronomer. Our continuous, high-resolution spectral monitoring program yielded an amazing result: the highest rate of



The spectrum of ρ Cas around the Balmer Hα line of hydrogen. This spectral line forms over a large fraction of the upper atmosphere and continuously changes its shape. In the year before the outburst of mid-2000, the line revealed strong emission to the left of the Hα-absorption trough; emission at this side of the line is usually not observed in ρ Cas. The absorption trough is shifted to the right with respect to the center-of-mass velocity of the hypergiant (the vertical red line), which signals a strong collapse of the upper atmosphere. Since mid-2001, very strong emission reappeared to the left of Hα, but rapid changes in the past ten months imply a new, rapid phase of atmospheric expansion. Plot courtesy of the author.

their cores and eventually evolve from the hottest, bluest, type-O spectral class to become first blue supergiants and then to redder, cooler, type-M supergiants. Stars with forty to sixty solar masses loop back from their red-supergiant phase into hotter and smaller blue supergiants. Above sixty solar masses, stellar-evolution theory suggests that stars never reach cool spectral-class M and remain hot, extreme supergiants. These curious evolutionary loops are predicted only for luminous stars born with masses within a limited range.

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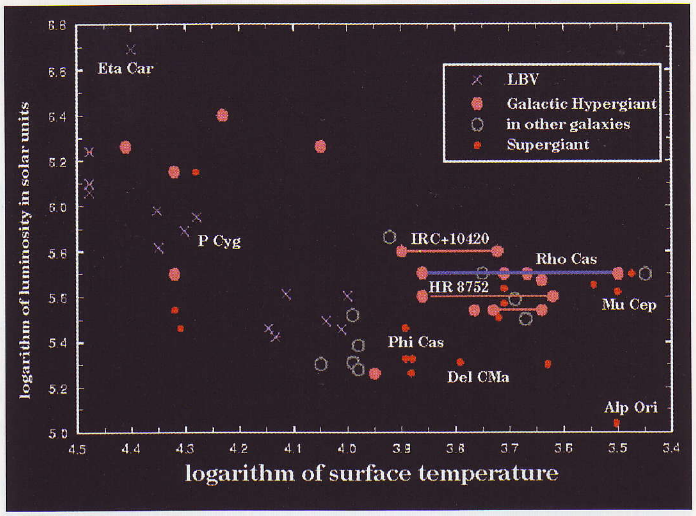
mass-loss by a star during a single outburst. At the same time, ρ Cas disclosed in an unequivocal way its true nature: it is a "yellow hypergiant." Our observations of the star have continued in the aftermath of the outburst, and the most recent spectral evolution reveals new, dramatic, dynamical changes in its outer atmosphere.

How Hyper is Your Giant?

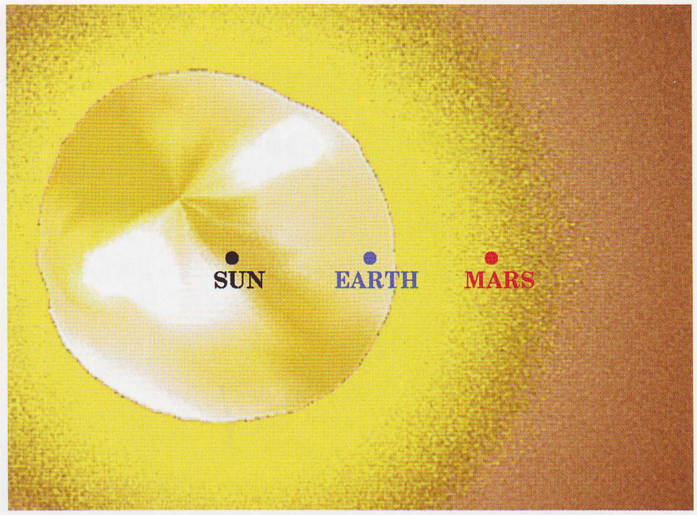
ρ Cas is among the most massive, cool stars presently known. Theoretical models employed to predict the evolution of very luminous stars indicate that the stars' lives are relatively short: the heavier a star is at birth, the sooner it dies with a blinding flash of light in a supernova explosion.

Indeed, different masses at birth spell different lives for stars. Stars with ten to about sixty times the Sun's mass burn hydrogen in

Evolutionary tracks for ρ Cas—with its total lifespan of ten million years, one or two million of which will be spent as a red supergiant—show that it is either becoming a red supergiant or is on its way back from being one. In general and after the hydrogen in their cores is depleted, stars begin fusing hydrogen to helium in a shell just outside their hot, helium-rich cores. Models predict that near the end of its red-supergiant stage, a massive star reacts to the constant drain of energy from this shell source of energy by raising its central temperature to more than 100 million kelvins and initiating the fusion of the core helium into carbon. Following an extended period of different nuclear fusion regimes (e.g., carbon fusion, oxygen fusion, etc.) and concomitant structural changes, the outer layers of the red supergiant contract, which increases the surface temperature. The red supergiant is now evolving "blueward."



Here are a number of super- and hypergiant stars according to their surface temperatures and luminosities. The cool luminous stars' surface temperatures marked in the right-half of the figure are below 10,000 K. Stars on the left side are hot (blue) luminous stars. The surface temperatures of the yellow hypergiants ρ Cas, HR 8752, and IRC+10420 change over time, marked with horizontal lines between the observed minimum and maximum temperatures. The blue horizontal line for ρ Cas represents the temperature change from about 7500 K to below 4000 K observed over roughly 200 days during the eruption of 2000. Plot courtesy of the author.



An artist's impression capturing the linear dimension of ρ Cas. The hypergiant has an average radius 400 to 500 times that of the Sun, so large that if placed at the Sun's position, ρ Cas's photosphere would extend beyond the orbit of Mars. The photosphere of the star oscillates by deforming from its normal spherical shape over a period of about one year. The outer atmosphere extends even farther out and pulsates over a longer period of time than the lower atmosphere. Illustration courtesy of the author.

This scenario is rather sketchy because we know that red supergiants are convective, large quantities of energy carried by hot parcels of gas from a star's depths to its surface, and release enormous amounts of atmospheric gas into space. Consider, for illustration, that M-class supergiant Betelgeuse, which if placed at the Sun's position would have a surface somewhere between Mars's and Jupiter's orbits, sheds each year about a millionth of a solar mass; the mass loss comes from steady wind leaving the star's huge surface. Red supergiants are, therefore, one of the most important cosmic factories for replenishing the interstellar medium with material processed through nuclear fusion reactions. More specifically in this case, the copious loss of mass from a cool luminous star is believed to have a decisive influence on the star's blueward evolution, which may last only as long as 50,000 years, less than one percent of the star's entire lifetime.

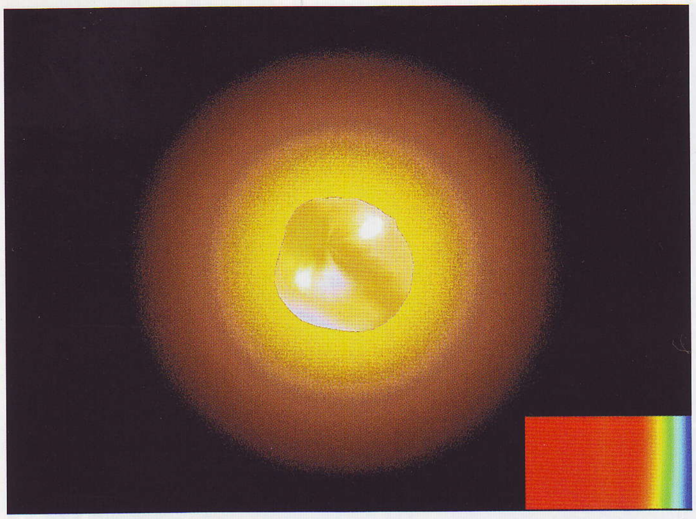
"Red supergiants are cosmic factories for replenishing the Universe with material processed through nuclear reactions"

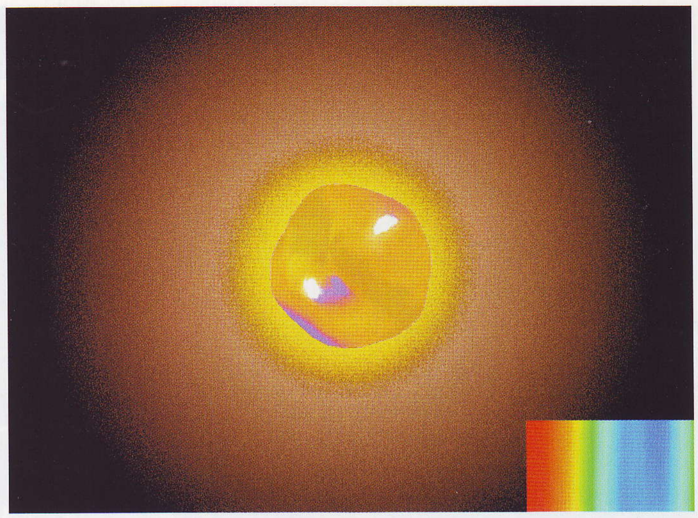
Only a handful of cool luminous stars known in the Milky Way Galaxy are thought to be post-red supergiants, and they are notorious for their changing spectral properties. HR 8752, for example, is a cool hypergiant that increased its surface temperature by 3000 kelvins over the past thirty years, while the temperature of star IRC+10420 increased at least 2000 kelvins over the last two decades. It is presently unclear if such large temperature changes can be directly attributed to active reconstruction of the stellar interior on human time scales, but the stars' spectra do indicate a very advanced evolutionary stage.

Mysterious ρ Cas is even more extreme. It usually has an optical spectrum corresponding to a surface temperature of about 6000 to 7000 kelvins and with unusually broad absorption lines not commonly observed in the spectra of other, "normal" yellow supergiants such as δ Canis Majoris and φ Cassiopeiae, which have luminosities comparable to ρ Cas. As with ρ Cas, the visual brightness of these supergiants fluctuates somewhat due to oscillations of the stellar atmosphere, yet ρ Cas differs in that it frequently shows very strong emission components in an important line in the red part of the spectrum.

This spectral line, called Balmer Hα and corresponding to a wavelength of 6563 Å, is produced by atomic hydrogen gas, the most abundant chemical element in the star's pulsating atmosphere. The line's shape provides us a precise indicator for gas movements in the extended hypergiant atmosphere, where it forms. The emission-portion of the Hα line is caused by Doppler-shifted photons from a strong stellar wind, indicative of a very high rate of mass loss. Indeed, before ρ Cas's dramatic dimming of 2000 my group occasionally measured mass-loss rates a hundred million times higher than that observed for the Sun's solar wind.

The broad absorption lines of ρ Cas are formed by supersonic, turbulent gas movements. Spectral changes indicate the star's atmosphere is very unstable, with surging upward and downward currents of material, a strong stellar wind blowing material outward, and other atmospheric activities that together give rise to pulsations





Another artist's impression of ρ Cas, illustrating in this case the hypergiant's large-scale, atmospheric pulsations. We infer such motions using changes in position of a neutral, photospheric iron line. When the atmosphere collapses, the absorption line is Doppler-shifted toward longer wavelengths; when the atmosphere expands, the line shifts toward shorter wavelengths. The line's shape and intensity also change due to variations of the density and temperature in the gas layers where the spectral line is formed. Illustration courtesy of the author.

of the surface temperature, brightness and size, in quasi-regular periods of about 320 days. During ρ Cas's pulsations in surface temperature of about 750 kelvins, the average radius of its visible surface changes by forty percent and averages a mean size of 400 to 500 times the radius of the Sun.

ρ Cas is, thus, smaller than red supergiant Betelgeuse with a mean radius around 700 times the Sun's radius. But Betelgeuse is not a hypergiant. The term "hypergiant" does not refer to the large size or luminosity of a massive star, but instead to its exceptional spectral properties indicative of a distended and dynamically active atmosphere. One out of a million stars in our Galaxy is a normal supergiant star, yet fewer are hypergiants. And the cool hypergiants are extremely scarce, their erratic atmospheric behavior thought to result from their advanced evolutionary stage on a blueward loop. They are so luminous that one cool hypergiant has even been identified in the spiral galaxy M33.

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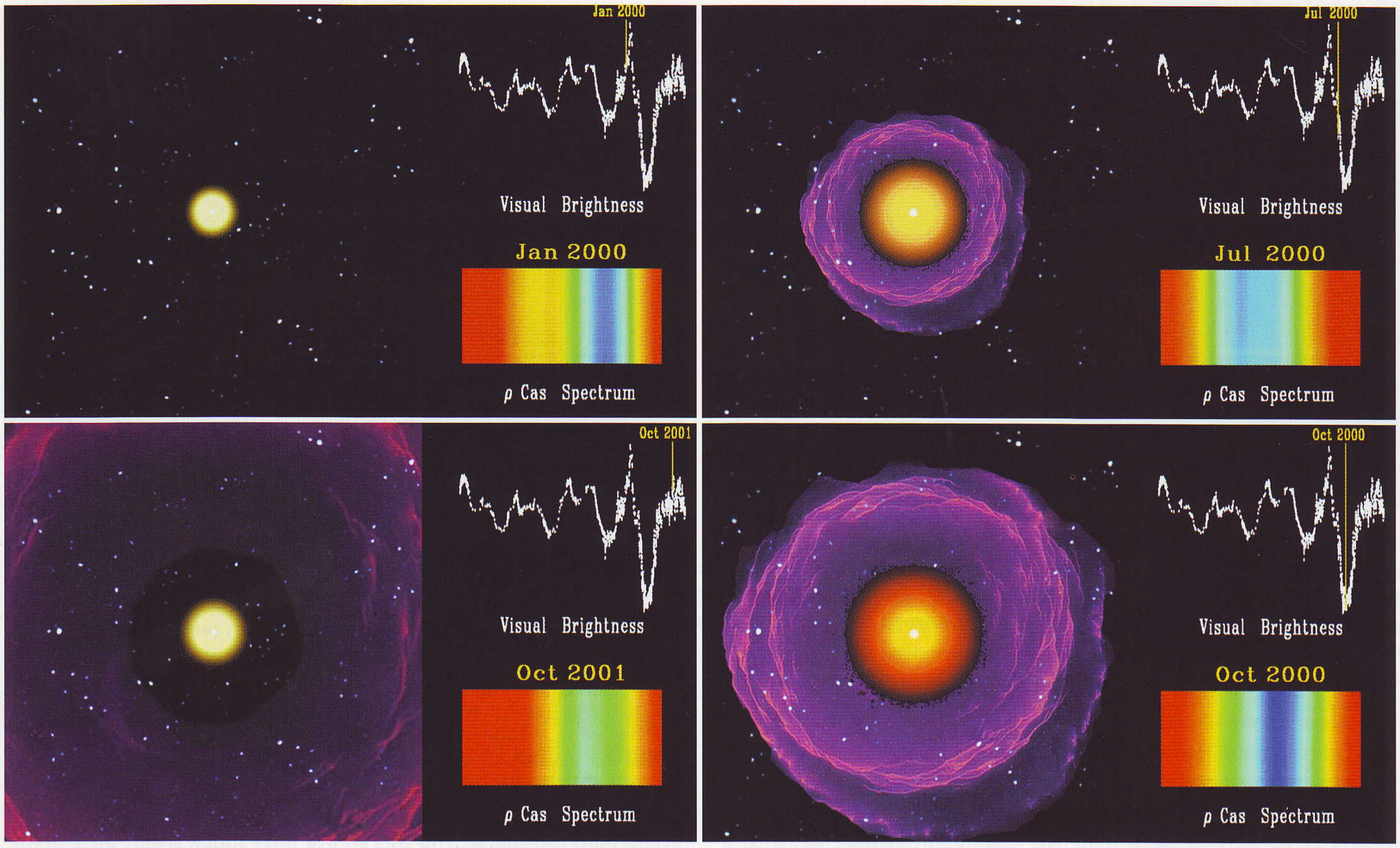
Mysterious Changes

In the summer of 1946, ρ Cas dimmed by 1.5 magnitudes to become fainter than 6.0 magnitudes. During this unexpected event, the star temporarily changed its spectral class from F to much cooler M and showed prominent spectral absorption bands attributed to titanium-oxide molecules, whose presence signals low atmospheric temperature. Such broad absorption bands are common for the optical spectra of M-class stars, such as Betelgeuse and μ Cepheus, but are absent in spectra of F-class stars. During ρ Cas's 1946 event, more than spectral changes were observed: the atmosphere's average temperature decreased by more than 3000 kelvins, causing the star to dim in the visible but to brighten in the infrared. The visible dimming lasted for about 400 days, and the star returned to normal brightness levels in late 1947. Spectra from this period clearly show absorption lines that are Doppler-displaced toward shorter wavelengths during the brightness decline, signaling atmospheric gases rushing outward. However, these old spectroscopic data are rather coarse and too sparse, and we can not infer much about the dynamics or thermal conditions in ρ Cas's atmosphere during this historical eruption.

Since that time the quality of spectroscopic measurements has improved considerably. Over the past ten years we collected from ρ Cas a total of about 100, high-resolution, optical spectra on different nights. The combined data sets yield the surprising result that the visual brightness changes of ρ Cas are, in fact, matched by Doppler shifts observed in the photospheric spectral lines about one hundred days earlier. In other words, the upward and downward movements of atmospheric gases are mimicked by intensity variations of continuous light emission from the star due to temperature changes in the lower atmosphere. In general, when ρ Cas's atmosphere collapses, it heats up over the following three months. After re-inflating, it cools down again.

In early 2000 large shifts of the absorption lines showed that the atmosphere was strongly collapsing. Roughly one hundred days later the brightness reached an unprecedented 4.0 magnitudes. Over the following hundred days, ρ Cas's atmosphere expanded, reaching a maximum velocity of about 35 km/sec in a massive eruption, and subsequently chilled by at least 3000 kelvins later that year. We were able to measure the wavelength shifts of the newly formed titanium-oxide bands: the combined measurements reveal that 10,000 Earth masses of gas were blasted off into space over a period of 200 days.



An artist's rendition of the millennium outburst of ρ Cas. Clockwise, from upper left: in January 2000 the brightness increases rapidly due to the strong collapse of the lower atmosphere; the surface temperature rises above 7000 K. In early to mid-2000 the atmosphere rapidly expands while the spectrum shifts toward shorter wavelengths. The outer atmosphere accelerates supersonically and is partly expelled into space. The entire upper atmosphere begins to quickly cool, changing the star's color yellowish-white to orange. In summer and fall of 2000 the temperature in the outer atmosphere decreases below 4000 K. New molecules can then form and appear in the optical spectrum. Meanwhile, the lower surface starts to retreat and the spectrum shifts back toward longer wavelengths. The cool circumstellar gas shell expands further, possibly becoming detached one year later, while the atmosphere contracts and the hypergiant's brightness and surface temperature increase to their levels before the outburst. Illustration courtesy of the author.

Many other strange features are observed in the outburst spectra from 2000, such as peculiar and normally absent (save for the 1946 eruption) emission lines of sodium. The most striking feature, however, is the broad, red-shifted Hα absorption line that shows emission at its short-wavelength side. The emission component is very strong in the months during the collapse and before the visible outburst but disappears completely during the deep dimming of ρ Cas.

"measurements reveal that 10,000 Earth masses of gas were thrown off by ρ Cas in just 200 days"

From this profound and time-dependent spectral line shape, we infer that the star's entire upper atmosphere falls down onto the star's photosphere, which subsequently warms under the strong compression. Further, our spectral monitoring of the Balmer Hα line reveals that high layers of the atmosphere oscillate with a longer period than those lower. As the gas shoots upward from deep atmospheric layers, it temporarily exceeds the gravitational pull of the star; some of the gas escapes into the environment around ρ Cas.

The energetics of the massive gas layers expelled from the star are subtle but very important. Freed atoms can bind into molecules such as titanium oxide, and, as the ejected layers expand and cool, free protons and electrons recombine into neutral hydrogen atoms. Both these combinations release energy to the ejected layers, which results in an increase in the layers' expansion velocity. Detailed calculations show that the hydrogen recombination mechanism is very effective in accelerating the explosion of the atmosphere of a yellow hypergiant, leading, in fact, to what we call a "superwind" from the star. The outburst results from the synchonization of outward acceleration with the thermal cooling rate, causing an avalanche of hydrogen recombination. A similar recombination mechanism for helium atoms is a possible cause for the faster eruptions of the smaller R Coronae Borealis stars. And in the spectra of RV Tauri variables, titanium-oxide bands reminiscent of those in ρ Cas appear during brightness minimum, whereas strong Hα emission occurs during brightness maximum. Stars of this type are also semi-regular pulsators and possess spectra that can vary between spectral classes F-G and K-M. Yet even though their spectral changes suggest kinship with the yellow hypergiants, these stars far less massive and smaller than ρ Cas.

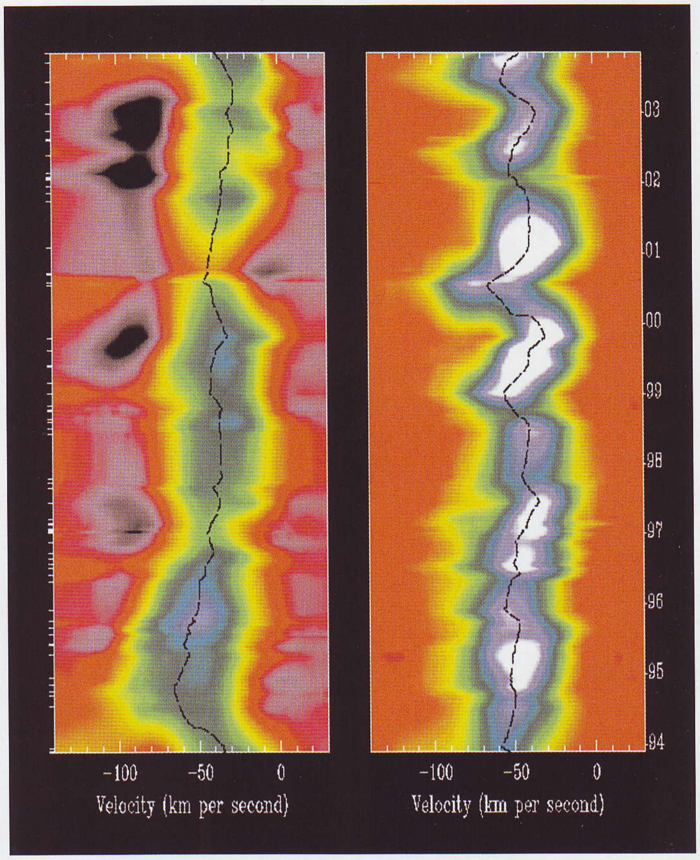
The advanced evolutionary stage of all these cool-star types indicates a prominent atomic process that strongly enhances the elasticity of the stars' dynamic atmospheres. Pulsations in deep levels of the atmosphere can become amplified and grow into circumstellar shock waves that strongly inflate and cool the upper atmosphere. Outburst spectra of ρ Cas reveal that its atmosphere more than doubles in size, and then retreats during about three months after the shell ejection.

Keeping Our Eyes Peeled

Over the past three years, the bright emission at the short-wavelength side of ρ Cas's Hα line has reappeared with an unusually broad absorption trough, signaling the collapse of the star's extended upper atmosphere. This peculiar Hα profile was also observed in ρ Cas before a moderate brightness decrease in 1986, but it has never been observed over a period this long. The recent spectral velocity measurements reveal that since early 2003, layers of the deeper atmosphere were rapidly expanding but did not reach the very fast expansion velocities observed during the millenium outburst. The lower photosphere started to contract quickly again in the fall of 2003, so we have not observed a new eruption as we imagined we might.

Our continuous monitoring reveals, however, a new, strange, spectral phenomenon. The shape of the Hα line has rapidly and dramatically transformed during the past ten months, signaling that the upper atmosphere reversed from contraction into a fast global expansion with enhanced mass loss. This remarkably fast phenomenon has not before been observed in ρ Cas or in any other star. We are left wondering what is in store for ρ Cas in the coming months—could the millennium eruption have been only the precursor of a stronger eruption still preparing to blow?

The critical thing for my group to do is to continue our monitoring of ρ Cas. When a new outburst occurs, we must collect high-quality spectra during the star's fast brightness decrease because they will provide important clues to and information about the acceleration mechanism of the atmosphere, and, more generally, such observations will help us uncover the physical mechanisms that instigate and drive these gargantuan stellar explosions. In addition, our and others' continued studies of cool hypergiants like ρ Cas will address the basic question of why these stars are rare compared to the blue luminous stars. Finally, our work will hopefully permit us to say how hypergiants end their stellar days—through a series of mass-losing eruptions separated by half centuries and occurring over a few tens of millennia or perhaps as super- or even hypernovae. All we can do is wait. And keep an eye on ρ Cassiopeiae. m



Dynamic spectra of the Balmer Hα line of hydrogen (panel left) and of a photospheric, neutral iron line (panel right). Line profiles are linearly interpolated between consecutive observation nights in the past decade, marked with the left-hand tickmarks. Each new calendar year is shown on the right. Dashed white lines trace the average atmospheric velocity determined from line shifts. Notice the strong blue-shift of the iron line during the mid-2000 outburst, which is preceded by strong emission (white spots) in the short-wavelength wing of Hα while the absorption core extends longward and the photospheric iron line strongly red-shifts. A collapse of the upper and lower atmosphere precedes the outburst. Observed over the past months is expansion of the upper Hα atmosphere with emission in the long-wavelength line wing. Plot courtesy of the author.

"could the millennium eruption have been only the precursor of a stronger eruption still preparing to blow?"

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