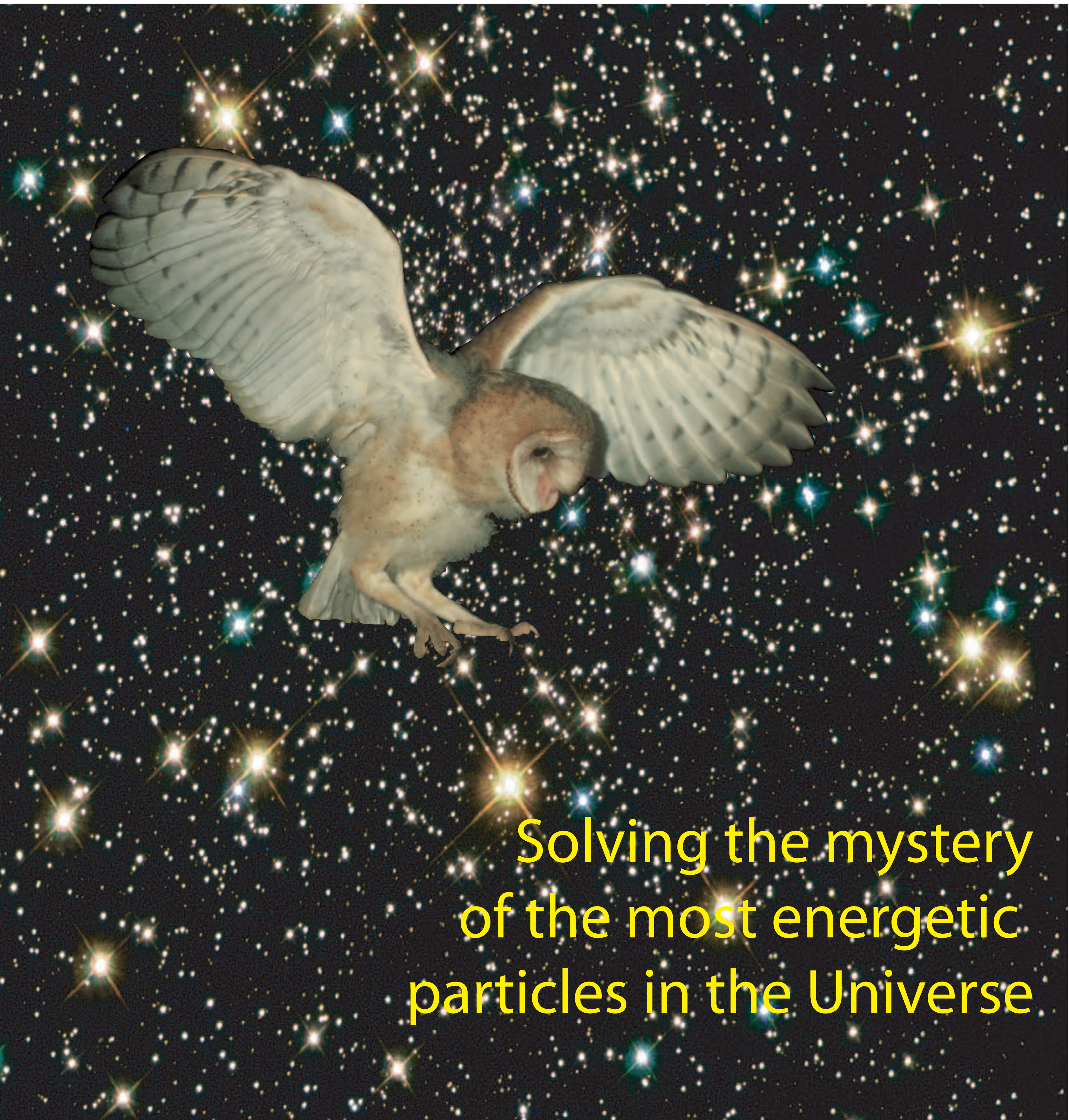
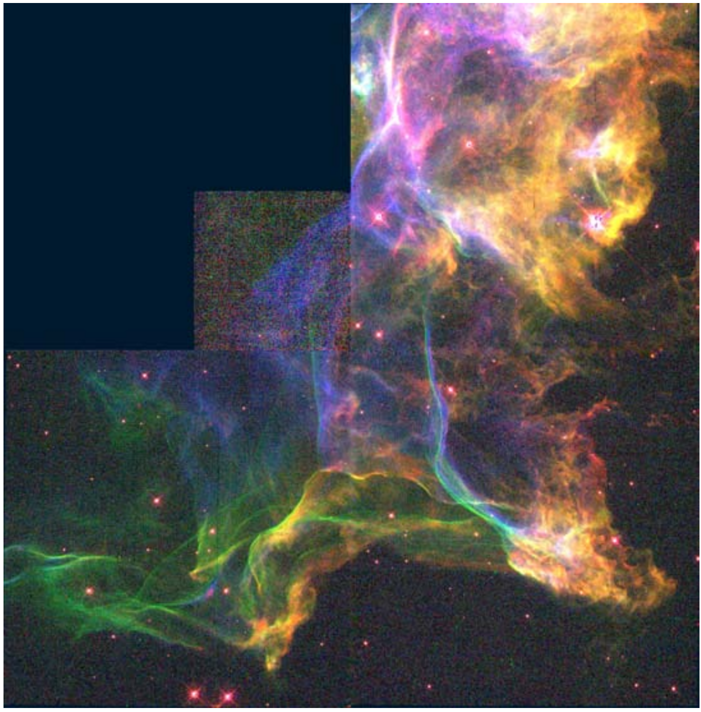
The OWL Mission



Solving the mystery
of the most energetic
particles in the Universe

> *What structures could possibly generate particles with such energy? Spinning supermassive black holes? Defects in the fabric of space? Exotic new physics involving hidden dimensions?*



NASA/HST

An Enduring Cosmic Mystery

Ultrahigh-energy cosmic rays are the most energetic bits of matter known, flying through space at velocities a fraction shy of light speed. The sheer energy they possess -- over a hundred million times more energy than that which can be produced in the best particle accelerators -- has defied explanation since their discovery 40 years ago.

A worldwide effort is now underway to solve this intriguing mystery. As messengers from beyond the Milky Way galaxy, these particles provide unique insight into the fundamental properties of matter, energy, space and time.

What structures could possibly generate particles with such energy? Spinning supermassive black holes? Defects in the fabric of space from trapped high-density regions of the early Universe leftover from the Big Bang? Exotic new physics involving hidden dimensions?

The OWL mission aims to find the origin of ultrahigh-energy cosmic rays, so rare that they strike the Earth's atmosphere at a rate of only one per square kilometer per century. Building upon several generations of ground-based research, the space-based OWL will cast a virtual net nearly the size of Texas to catch these rare particles as they strike the Earth's atmosphere.

Cosmic rays have long been at the forefront of astronomy and physics, enticing scientists to study the highest-energy phenomena in the Universe a generation before we learned of celestial X rays and gamma rays. The cosmic-ray field has also produced several Nobel Prize winners, the latest of whom earned the 2002 Prize for neutrino physics. Now we are narrowing in on the ultrahigh-energy cosmic ray. What new insights and advancements will come from our pursuit?

Ultrahigh-Energy Cosmic Rays:

Unprecedented Insight into the Nature of Matter and Energy

When the new European particle accelerator comes online at CERN in 2007, physicists will have a powerful tool to crack open atomic nuclei and study the building blocks of matter and energy -- fleeting particles and elusive forces that reveal themselves only at terrific energies. By accelerating protons to near light speed and smashing them against each other, scientists will attain the TeV energy level, a thousand billion electron volts, an energy level that existed briefly after the Big Bang. This will be a monumental achievement, one that is uniting scientists in dozens of countries and will reveal untold secrets about the physical world in which we live.

Yet nature, as always, humbles us. Forces in the Universe are capable of accelerating particles to energies over a hundred million times greater than what CERN scientists will generate. Indeed, the Earth is bombarded with these particles daily in the form of ultrahigh-energy cosmic rays (UHECR). What phenomena generate such energetic particles, and what unique lessons can they teach us?

> *Nature, as always, humbles us. Forces in the Universe are capable of accelerating particles to energies over a hundred million times greater than what scientists can generate with the most fantastic human-made machines.*


NASA/HST/CXC

The Cygnus Loop (left) and the Crab (above) are two examples of nature's powerful particle accelerators. Something even more powerful is creating UHECRs.

OWL (Orbiting Wide-angle Light collectors) is a proposed space-based mission that will determine the energy, direction and interaction characteristics of large numbers of these particles. Nothing short of the extraordinary must be involved in the creation of UHECRs, for their energies are simply too immense to originate in star explosions or solar activity, the source of lower-energy cosmic rays. Theorists suggest that UHECRs may be harbingers of new physics, associated with hidden dimensions, or generated in high-density trapped defects of space leftover from the Big Bang.

This booklet describes the history and current search for UHECRs and the contributions that OWL will make to the field. UHECRs represent an intriguing mystery in physics and astronomy, and solving this mystery will lead to profound, new insights in our understanding of nature.

Hall-of-Fame Fastballs

The ultrahigh-energy cosmic rays, those above 10^{20} electron volts, carry the kinetic energy of a major league fastball. Seeing how all that energy comes from a single fast-flying subatomic particle, that's one powerful pitch. UHECRs are traveling over 99.99999999999999999999 percent light speed.

What is so perplexing is that, from what we understand about physics and the Universe, we shouldn't be seeing many cosmic rays above about 5 x 10^{19} eV, yet we do.

The Universe is rich with a variety of cosmic rays, which are actually not "rays" at all but rather particles -- for example, an electron, proton, neutrino or carbon nuclei -- moving at near light speed. By far, the most common cosmic rays are of low energy, at 10^6 to 10^9 eV, generated by the Sun. These are called Solar Energetic Particles, the bulk of which are electrons flung towards the Earth during solar flares, coronal mass ejections, or other solar events. Cosmic rays about a million times more energetic than these, up to about 10^{15} eV, are likely associated with star explosions, or supernovae. These particles are among the few samples of matter we have from beyond the Solar System. A supernova might fire these particles from the guts of stars to cosmic-ray energies immediately, like shrapnel; or shockwaves from the explosion may accelerate particles already floating in the interstellar medium. Many cosmic-ray experiments attempt to find the origin of these cosmic rays and also map the distri-

The Cosmic-Ray Energy Scale

Cosmic-ray energy is commonly measured in electron volts. The study of cosmic rays is one of the few disciplines that traverses such a wide swath of energy, over fifteen orders of magnitude.

electron volt (eV) -- the energy of light particles that the Hubble Space Telescope sees; 13 eV are needed to pull an electron from a hydrogen atom

kilo-electron volt (keV) -- a thousand electron volts, 10^3 eV, typical energy of an X ray

mega-electron volt (MeV) -- a million electron volts, 10^6 eV; in the Sun, through the process of nuclear fusion, four nucleons are fused into a helium atom to release 25 MeV

giga-electron volt (GeV) -- a billion electron volts, 10^9 eV, typical energy limit of cosmic rays from the Sun

tera-electron volt (TeV) -- a trillion electron volts, 10^{12} eV, nearly the highest energy attainable so far with human-made particle accelerators

peta-electron volt (PeV) -- 10^{15} eV, probable energy limit for cosmic-ray electrons from supernovae such as the Crab Nebula; the energy goal of the next generation of particle accelerators now under construction

exa-electron volt (EeV) -- 10^{18} eV, pretty powerful

zetta-electron volt (ZeV) -- 10^{21} eV, the realm of the highest-energy cosmic rays known, the UHECRs

yotta-electron volt (YeV) -- 10^{24} eV, several thousand times more powerful than the highest-energy cosmic ray detected; the tip of the metric system too

The HiRes observatory lies in the Utah desert, comprising a ring of detectors on two plateaus (left). When the Sun goes down, the doors are lifted to expose the HiRes mirrors (middle). Ultrahigh-energy cosmic rays interacting with material in the atmosphere create a fluorescent disk, which travels downward. This results in the generation of ultraviolet light, which these mirrors reflect onto special detectors. The Auger Observeratory, under construction on the high western plains of Argentina, employs similar detectors placed across hundreds of kilometers and also relies on a second kind of detector (right).

bution of elements. High-energy cosmic rays, from about 10^{15} to 10^{19} eV are rare, and their origin is also unknown. Yes, yet another mystery. But unlike the UHECRs, the high-energy variety does not require possible new laws of physics to understand their nature.

Exploring the Highest Energy Frontier

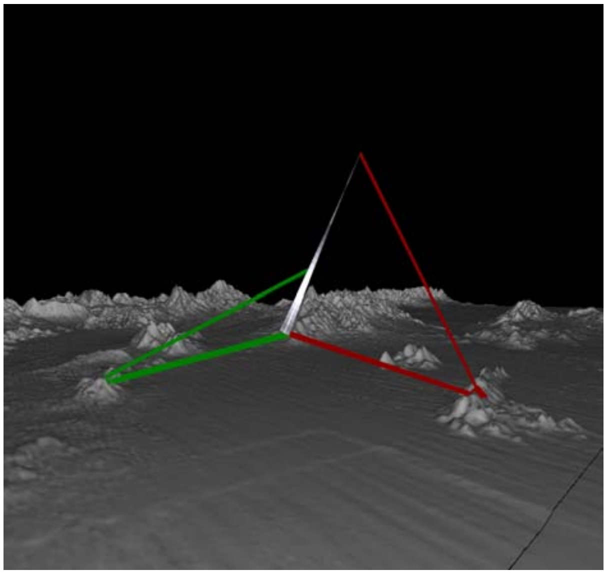
The UHECRs are the rarest of the bunch but undeniably real. What is so perplexing is that, from what we understand about physics and the Universe, we shouldn't be seeing many cosmic ray above about 5×10^{19} eV. Accelerating a particle to such high energy requires a tremendous generator. Ordinary star explosions simply aren't powerful enough to do the job. The Milky Way galaxy is home to many spinning, stellar-size black holes. Even these monsters aren't powerful enough to whip a particle to the UHECR level. A supermassive black hole could do it. These are objects in the center of galaxies containing the mass of millions to billions of suns all compressed into a region about the size of our Solar System. However, such a supermassive black hole would need to be relatively close to us, within 300 million light years. A cosmic ray traveling farther than 300 million light years would slowly lose energy as it treads through the fog of radiation and dust that fills the Universe. Current theories state that distant cosmic rays would be seriously depleted above about 5×10^{19} eV. There are indeed relatively nearby supermassive black holes, but none appears active enough to shoot out UHECRs.

OWL is a bold, new approach, a culmination of nearly 20 years of experimentation, and scientists expect nothing short of a windfall of data.

There are two main ways of detecting UHECRs. A high-energy cosmic ray will collide with particles in the Earth's atmosphere and produce a cascade of secondary particle collisions and a characteristic ultraviolet burst of light. That initial cosmic ray is destroyed before reaching the Earth's surface. Ground-based instruments either track these secondary particles through the atmosphere by the ultraviolet light signal or detect the particles when they reach the ground, and then reconstruct information about the powerful particle that caused this "air shower." The UHECRs are so rare, however, that detectors must spread out on the ground to cover a wide patch of sky to catch the secondary particles or observe the flash of light. While lower-energy cosmic rays bombard every inch of the Earth every second, a UHECR will strike at a rate of about one per square kilometer per century. That's not very often. Ground-based detectors covering or observing many square kilometers have to wait years to catch but a few UHECRs. Each new event is hot news, exciting scientists around the globe.

Alas, this paucity of data is the major problem facing UHECR research. Scientists currently have no more than a dozen UHECR events to study. The actual number of UHECR events is currently debated, with conflicting arrival rates seen by the two major ground-based detectors: the High-Resolution detector (HiRes) in Utah using the UV light detection method, and the Akeno Giant Air Shower Array (AGASA) near Kofu, Japan, using the ground particle detection method.

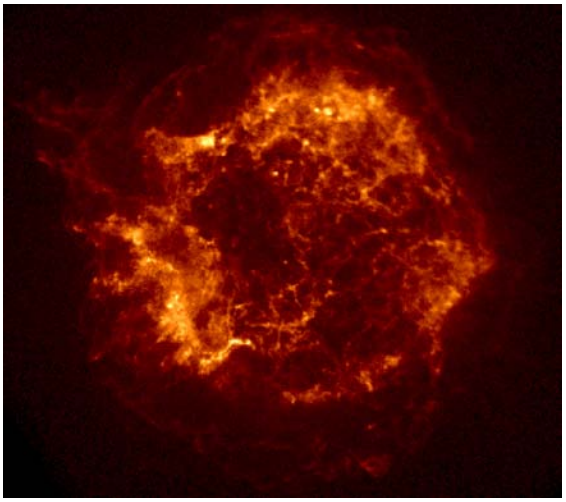
OWL is a bold, new approach, a culmination of nearly 20 years of experimentation, and scientists expect nothing short of a windfall of data. OWL systematically builds upon a pioneering series of UHECR detectors: HiRes and its famous predecessor, the Fly's Eye, and AGASA. It will also benefit from a larger ground-based effort under construction in Argentina called the Auger Observatory, which will utilize both the ground particle detection and UV light methods. A proposed mission to be placed aboard the International Space Station, called the Extreme Universe Space Observatory (EUSO), would have an aperture larger than any existing detectors on Earth. With its monocular detection capability, EUSO may serve as a first generation pathfinder in going from concept to technical reality. OWL, with its binocular vision and larger aperature, would be a more powerful detector to explore the frontier beyond the GZK limit (see below), as well as to search for ultrahigh-energy neutrinos, exotic particles which can travel through the whole Universe unscathed.



A computer reconstruction of an actual air shower event over Utah. The incoming UHECR initiated a cascade of secondary collisions. The two sets of HiRes detectors, shown here in red and green, captured the air shower in "stereo," shown in white. The detectors are 12 kilometers apart. Courtesy R. Wayne Springer and HiRes team.

You Can't Get Here from There!

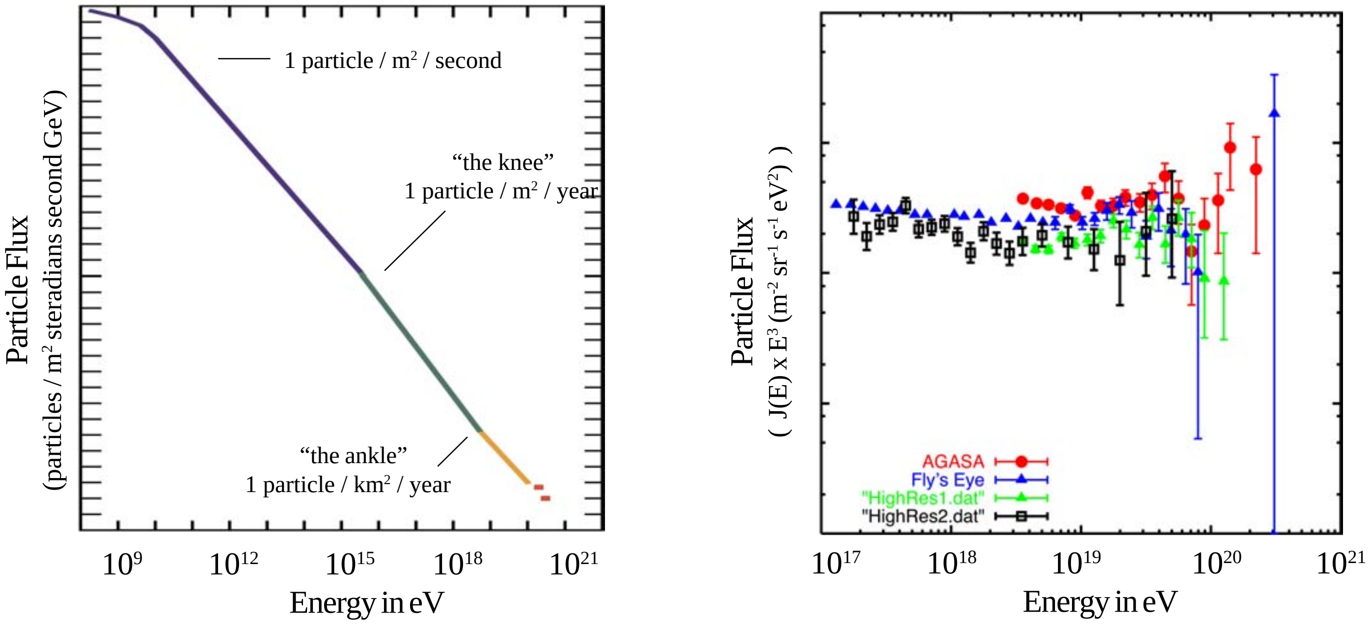
UHECRs present a cosmic Catch 22. As noted earlier, the source of particles greater than about 5 x 10^{19} eV should be within a horizon of about 300 million light years from Earth, for particles from beyond this distance would lose energy on the long journey, essentially by smashing into particles of light (photons) that fill the Universe. Yet scientists have been hard pressed to find a source within 300 million light years that could accelerate particles to such extreme energies. This boundary of the UHECR horizon is rooted in a predicted phenomenon called the GZK effect, proposed by American physicist Kenneth Greisen and two Soviet physicists, Georgi Zatsepin and Vadim Kuz'min in 1966.



The star that exploded to produce the lovely Cassiopeia A supernova remnant, as imaged here by the Chandra X-ray Observatory, is likely the type of source generating high-energy cosmic rays.

The Universe is bathed in a sea of cosmic microwave photons, about 400 for every cubic centimeter. This is the afterglow of the Big Bang. According to Albert Einstein's Theory of Special Relativity, to a UHECR particle moving at near light speed, these low-energy photons are seen as high-energy gamma rays.

Greisen, Zatsepin and Kuz'min calculated that the highest-energy cosmic rays would readily encounter these microwave photons and lose about one-fifth of their energy with each collision. These collisions would occur at a rate of about one per 20 million light years. So gradually, the battered cosmic ray loses more and more energy. Few particles are expected to reach us above 5x10^{19} eV (the GZK cutoff), and many UHECRs that started out at higher energies should be seen to pile up at an energy of about 4x10^{19} eV (the GZK pile-up).



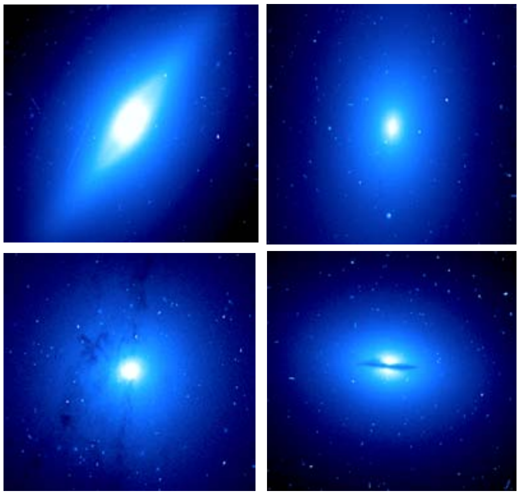
Lower-energy cosmic rays are clearly more common than higher-energy ones, yet there is a change in the rate of detection around 10^{15} eV and then again above 10^{18} eV. Scientists call these the cosmic ray "knee" and "ankle," respectively (left). The OWL mission will examine the ankle (right). Data from AGASA in Japan suggest that the flux of cosmic rays above 10^{19} eV actually starts to increase again. Yet data from HiRes in Utah suggest the flux drops off after 10^{19} eV. AGASA and HiRes employ different types of detectors. Note the large error bars, that is, large level of uncertainty. OWL will supply an abundance of data and narrow the error bars considerably. It will also look for UHECRs well above the GZK energy of 5×10^{19}eV.

Yet scientists have detected particles as high as 3×10^{20} eV in energy. Were they incorrectly measured? Are we witnessing a violation of the GZK effect? Or, is there some local, hidden source of cosmic rays? The OWL mission aims to find out. Today, the theories of UHECR origin are based on these questions.

UHECR Energy: From Below or Above?

UHECRs are generated either "bottom-up", "top-down" or involve new physics. We don't know which. In the bottom-up scenario, particles don't start out fast. Their velocity and energy are boosted by naturally occurring cosmic accelerators. A spinning, supermassive black hole could do this. Although notorious for pulling matter in, black holes often shoot particles away in high-speed, collimated jets. The process involves strong magnetic fields around the black hole. A particle falling into a black hole can get caught up in such a magnetic field and, through a process not well understood, fly off in a jet perpendicular from the flow of matter into the black hole.

Scientists have identified several relatively nearby supermassive black holes that could possibly accelerate particles to the UHECR level, but there is not enough data to confirm this. Part of the problem is that, unlike light, UHECRs do not follow a straight path from their origin to Earth. Their journey might involve twists and turns, the result of encountering magnetic fields deep in interstellar and intergalactic space. So it is difficult to conclude that the few UHECRs collected point to these supermassive black holes. It could be just a coincidence. Another bottom-up source could be magnetars, which are highly magnetic neutron stars within our Milky Way galaxy. The magnetar, spinning over a thousand times per second, could whip up gas around the star to high speeds and ultimately accelerate some particles to very high energies. Again, there is no observational evidence to support this.



Some scientists suggest that ultrahigh-energy cosmic rays originate in relatively nearby, “retired” quasar galaxies, such as these four galaxies located in the direction of the Big Dipper. These galaxies are thought to contain once-active but now extinct quasars. (NASA/HST/Hamilton)

How to Make a UHECR

Bottom-Up - Top-Down - New Physics

BOTTOM-UP
active “black hole” galaxy -- shock acceleration in the radio lobe: OWL will search for specific sources and look for events beyond the nominal GZK cutoff
gamma-ray burst -- shock acceleration: OWL will search for isotropy of UHECRs; GZK cutoff is present
local “retired” quasar remnant -- acceleration by supermassive black hole magnetic fields: OWL will search for specific sources and look for events beyond the nominal GZK cutoff

TOP-DOWN
dark matter -- decay of massive particles: OWL will search for anisotropy of UHECRs
topological defects -- spacetime knot “unravels”: OWL will search for isotropy of UHECRs plus excess neutrinos and gamma rays
Z-burst -- ultrahigh-energy neutrinos interact with “local”relic antineutrinos: OWL will search for anisotropy of UHECRs plus excess neutrinos and gamma rays

NEW PHYSICS
Lorentz-invariance violation -- relativity not valid at ultrahigh energies: OWL will search for higher-energy GZK cutoff
extra dimensions -- neutrino cross-section increase: OWL will search for excess neutrinos

The top-down scenario places the UHECR search on the frontiers of physics. Top-down sources involve dark matter, trapped defects in space, string theory, hidden dimensions, the unification of fundamental forces. With the OWL mission identifying perhaps hundreds of UHECR events per year, scientists will at long last have sound observational evidence to explore these cutting-edge concepts.

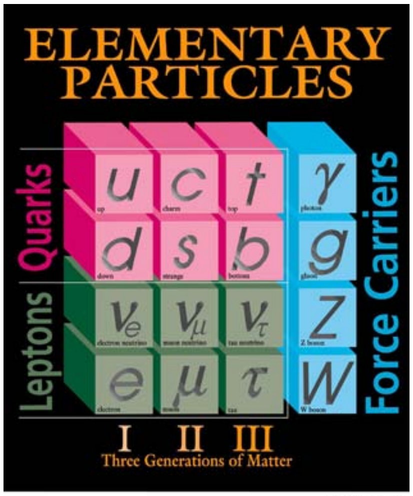
> *OWL may be able to measure the distribution of dark matter by mapping the distribution of cosmic-ray production.*

Exploring for New Physics

Let's back up a bit. A major effort is underway to fold Einstein's General Relativity (the theory of gravity and the large scale) into Quantum Mechanics (the theory of the subatomic) in order to create a single, unified theory of space, time, matter and energy. String theory is the name given to one such effort.

There are four fundamental forces in nature: gravity, electromagnetic forces, weak forces and strong forces. Quantum mechanics describes three of these forces, each with particles that transmit the force: photons (particles of light associated with electromagnetism), gluons (the strong forces binding atomic nuclei), and W and Z particles (weak forces seen in radioactive decay). Gravity, however, is more of a mystery. What is gravity's connection to quantum mechanics? Is there a gravity particle, called the graviton, and does it involve extra dimensions? UHECRs may provide some insight.

All of these forces may be revealed as one unified force at extremely high energies, such as the energy that existed at the Big Bang. In fact, physicists have already found that electromagnetic and weak forces are indistinguishable above about 200 billion eV -- energies now easily attained with particle accelerators. Scientists speculate that strong forces, too, can be unified with the "electro-weak" force at about 10^{24} eV. This energy level is known as the Grand Unified Theory (GUT) scale. Particles created at energies associated with the Big Bang that would exist at the GUT scale -- and thus provide evidence of a unified electromagnetic-weak-strong force -- may, theoretically, produce UHECRs above 10^{20} eV when they decay. That's where OWL comes in.



Fermilab, 1995

OWL data may find new particles and forces to add to the standard model of particle physics.

These GUT-scale particles, with exotic names such as leptoquarks and the GUT Higgs bosons, could form from topological defects created by the Big Bang. These defects are pieces of space left over from the Big Bang that may exist today and contain enormous energy densities. OWL's detection of UHECR neutrinos, as one example, may provide the first tangible indication of the existence of the unification of three of the four forces in the Universe.

Over 90 percent of the matter in the Universe is in a form yet to be detected directly, called dark matter. This type of matter doesn't seem to emit electromagnetic radiation like ordinary matter -- that is, the atoms from which all that we touch and see are made. One theory of dark matter poses that dark matter is a slowly decaying GUT-scale particle created in the Big Bang. This matter may form a halo around galaxies, including our own. As this matter decays or annihilates (by colliding with other particles), it may produce UHECRs. OWL may be able to measure the distribution of this dark matter by mapping the distribution of UHECR production.

The OWL mission attacks the gravity mystery and the question of hidden dimensions through the detection of UHECR neutrinos. Scientists have only recently learned that neutrinos have mass but no charge. The rate of interactions of ultrahigh-energy neutrinos can be much larger than that calculated with known physics if the nature of gravity is determined by extra hidden dimensions.

What is gravity's connection to quantum mechanics? Is there a gravity particle called the graviton, and does it involve extra dimensions? OWL may provide some insight.

Although gravity keeps us pinned to the Earth, it is a relatively weak force compared to the other three fundamental forces. Indeed, we overcome gravity (albeit momentarily) by merely jumping, yet it takes terrific energy to break apart the strong forces of an atom. Gravity may be weak because part of the force "leaks" into other dimensions that we cannot perceive. If this is the case, some of that lost energy might be imparted to neutrinos, bulking them up to the size of a proton. To see this effect, very precise information is needed about the rate and energy of UHECR neutrinos -- the type of precision that only OWL can provide.

Among the Key Questions of Astronomy and Physics

The OWL mission, of fundamental importance to the fields of astronomy and physics, addresses four of the 11 questions posed by the National Research Council Committee on the Physics of the Universe in a report called “Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century” (also known as the Turner Report). This is the report that guides scientists in their pursuits at the beginning of this new century.

One of the 11 points in the Turner Report is the UHECR mystery itself, which OWL obviously addresses directly. The Report also asks: What is dark matter? What is gravity? and, Are there additional dimensions? OWL will provide insight to each of these mysteries as well.

Question 2. What is the dark matter?
As another “top-down” possibility, it has been suggested that the dark matter may consist of GUT scale supermassive particles with a long lifetime. These particles may slowly decay to produce the ultrahigh-energy particles observed. Alternatively, it has been suggested that their annihilation in a dark matter galactic halo may produce the ultrahigh-energy cosmic rays. In either case, asymmetries in the distribution of dark matter will be reflected in a measured anisotropy of the ultrahigh energy cosmic rays measured by OWL.

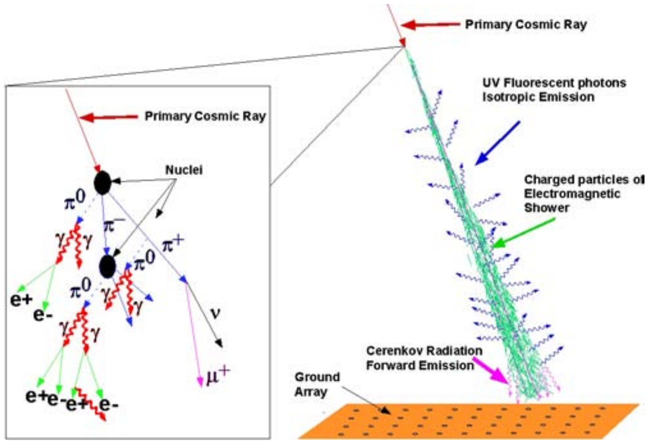
Questions 3 & 4. What is gravity? Are there additional dimensions?
These questions may be related because it has been suggested that the weakness of gravity compared to that of the other forces may be the result of a dilution caused by its propagation in extra dimensions that we do not directly experience in the macroscopic world. In such "Kaluza-Klein" type theories, the extra dimensions can result in extra degrees of freedom that allow neutrino cross sections to grow with energy to sizes approaching the scale of hadronic cross sections at ultrahigh energies. Ultrahigh-energy neutrinos have been predicted to be produced by the decay of the mesons produced by protons interacting with the 2.7K radiation (GZK-Stecker neutrinos), by the GUT scale decay processes discussed above, and by the production of high-energy mesons in astrophysical sources.

An "OWL’s-eye" View From Space

OWL's approach allows scientists to monitor at one time a huge swath of the sky, nearly as large as Texas.

OWL makes use of the Earth's atmosphere as a huge "calorimeter," or detector, in which the air showers induced by UHECRs develop and produce observable ultraviolet fluorescence. That is, each UHECR makes an ultraviolet “streak” as it plows into the atmosphere. So, instead of looking up at the heavens, the two OWL eyes look down at Earth for these UV streaks. A stereo measurement of this atmospheric UV fluorescence produced by air-shower particles is the most accurate technique that has been developed for measuring the energy, arrival direction, and interaction characteristics of UHECR in the atmosphere.

OWL employs a pair of formation-flying spacecraft in a low-inclination, medium-altitude orbit. Looking downward, the OWL instruments on each spacecraft view a common volume of the night atmosphere to search for the characteristic flash of ultraviolet light. This is a multi-part



The anatomy of an airshower: An "air shower" of particles originates when a high-energy primary cosmic ray interacts strongly with the nucleus of an atom in the atmosphere. From the energy of this interaction, many secondary particles are created. Some of these, the charged pi-mesons, may change their identities ("decay") or may continue downward and interact with another atomic nucleus, producing still more particles. The uncharged pions (pi-zeros) decay into gamma rays that in turn produce pairs of electrons and positrons, initiating an "electromagnetic shower". As generations of interaction take place, ultimately, the energy that initially was concentrated in the primary cosmic ray is shared by billions of charged particles traveling through the atmosphere as an air shower following the trajectory of the primary cosmic ray. The passage of these particles excites atmospheric nitrogen molecules that then emit ultraviolet fluorescent photons in all directions (isotropically). These are the photons observed by HiRes and Auger on the ground and OWL from space. They track the air shower development, allowing determination of its energy, origin-direction and interaction characteristics.

process. A UHECR's impact creates a cascade of secondary particles, the air shower. These secondary particles take the form of electrons, positrons (the antimatter form of an electron), and other particles. These particles interact with nitrogen molecules in the atmosphere, exciting the nitrogen and producing ultraviolet radiation. The fluorescence from a cosmic-ray-induced air shower appears as a luminous disk a few meters deep and almost a kilometer across, moving down through the atmosphere at near light speed. The brightness of the disk is determined by the energy of the incoming UHECR and changes rapidly as the air shower moves through the atmosphere. OWL fully characterizes these particle air showers by using the two instruments in stereo to measure their detailed temporal and spatial development. OWL's "stereo" viewing design, analogous to depth perception, provides for an accurate measurement of energy and direction of the fluorescent trail produced by the UHECR. Two eyes are better than one.

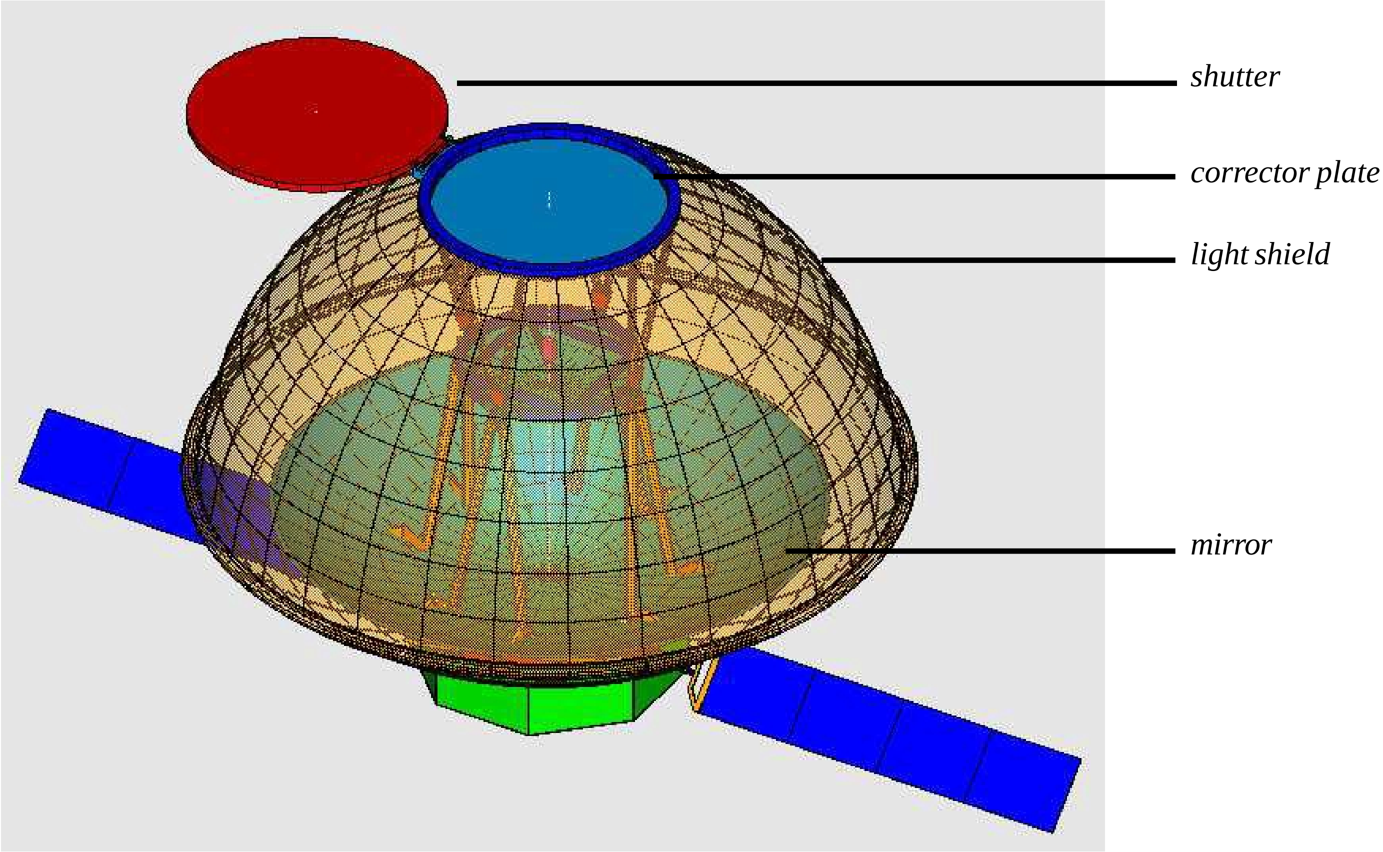
OWL's approach allows scientists to monitor a huge swath of the sky at one time, nearly as large as Texas. Whereas ground-based instruments can only detect a few UHECRs above 10^{20} eV a year, OWL is expected to see hundreds to thousands, depending on their true rate.

OWL Eyes

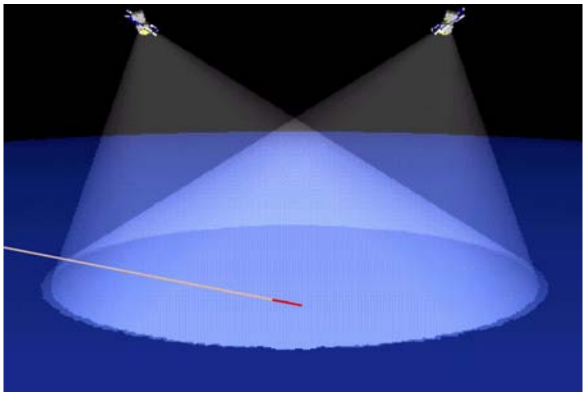
It's not easy to catch a disk of ultraviolet fluorescence that flashes through the night sky traveling at nearly the speed of light and lasts for only a few tens of microseconds. The OWL eyes orbit between 600 and 1,000 kilometers above the Earth at various points in their mission. This allows observation of vast volumes of the atmosphere, but it also means the UV fluorescence light, which is emitted equally in all directions by the atmospheric nitrogen, is diminished in intensity when it reaches an OWL eye. For this reason, the OWL eyes must be large to collect as much of the UV signal as possible. The baseline OWL instrument has a three-meter entrance aperture for collection of UV photons, and a seven-meter mirror for focusing an image of the night sky onto an array of detectors.

Flying the OWL Mission

To extract the most science from the OWL, the two OWL eyes will be configured in several orbits and separations during the OWL mission. At beginning of the mission, the two OWL spacecraft will be launched together in a single rocket, with the mirrors folded like petals and the detectors and other deployable elements packed closely. On reaching their 1,000-kilometer orbit, the two satellites are launched and the optical elements are deployed. In operation, the two OWL eyes function independently, observing the same volume of atmosphere but separately searching for and recording the UV flashes, identifying the event of an air shower induced by a UHECR. When the data from the two eyes are brought together, during later analysis, the full power of stereoscopic viewing can be brought to bear in reconstructing the energies, direction and development of the UHECR air showers.



The baseline OWL-eye instrument is a large f/1 Schmidt camera with a 45-degree full field-of-view (FOV) and a 3.0 meter entrance aperture. The entrance aperture is filled with a Schmidt corrector. The deployable primary mirror is 7 meters in diameter. The focal plane has an area of 4 m^2 *segmented into approximately 500,000 pixels distributed over 1,300 multi-anode photomultiplier tubes. Each pixel is read out by an individual electronics chain with a time resolution of 0.1 microseconds, and can resolve single photoelectrons. Taking into account obscuration by the focal plane and by the members supporting the focal plane and corrector plate, the effective aperture of the instrument is about 3.4* m^2*. A deployable light shield covers the instrument and a shutter is used to close off the aperture during non-observing periods. For clarity, the light shield is shown as translucent in this figure. A UV laser for atmospheric characterization is located at the back of the focal plane and fires through the center of the corrector plate to a small steering mirror system. Laser light reflected by clouds is detected and measured using the OWL mirror and focal plane.*



This simulation shows the two OWL satellites, in equatorial orbit, viewing a UHECR event over the Pacific Ocean. From its perch at 1,000 km, OWL monitors a circular region about 1,200 km across. The path of an incoming UHECR is shown in pink. As it hits the atmosphere, the cosmic ray creates an airshower of secondary particles, shown in red. This is the section of the path that OWL would see.

Following on-orbit checkout, in Phase I, the two satellites will fly in formation with a separation of 10-20 kilometers for about three months to search for signatures of a special category of neutrinos that pass through the Earth and initiate upward-going showers. The special UV light, called Cherenkov light, from one of these showers would be confined to a radius of perhaps 30 kilometers at the OWL eyes' orbit altitude. The OWL satellites are kept close together in this phase because the UV signal "signature" of these special showers can be confused with certain types of unwanted background events. But when both OWL eyes see the same signature of an upward neutrino-induced shower at the same instant, doubt is removed.

Following this period, in Phase II, the spacecraft, still at 1,000 km altitude, separate to 600 kilometers apart for about 2.5 years to measure the high-energy end of the UHECR spectrum, above 10^{20} eV. Here the OWL eyes will have their maximum ability to view large areas of the night sky. They will observe air showers from UHECR incident on the atmosphere from all directions. The aperture of each OWL eye, which is a measure of an instrument's ability to monitor both area and incident particle direction, will exceed 2 million square-kilometer-steradians (km^2-sr) while in full operation. Of course, there are many conditions in which OWL can't observe UHECRs because of background light, such as during the daytime, or even at night when there is too much from the moon or the city below. Taking account of these, OWL's effective "continuous-observing" aperture will be close to 230,000 km^2-sr. Also, certain types of clouds can interfere with OWL's view, decreasing the aperture further. For comparison, the effective aperture of the largest currently operative ground array, HiRes, is about 1,000 km^2-sr. When completed, the particle-detecting component of Auger will have an aperture of 7,000 km^2-sr.

The field of cosmic rays is no stranger to cutting-edge physics. The study of cosmic rays led to the discovery of antimatter, muons and neutrinos, all once in the realm of speculation. Opportunity knocks once again.

When the high-energy-observing Phase II is complete, the altitude of both OWL satellites will be reduced to 600 kilometers. Phase III, with a 500-kilometer separation, will measure the cosmic-ray flux at lower energies, above a few times 10^{19} eV. The periods spent at each altitude and separation can be adjusted as instrument condition and detection results dictate. *This flexibility to adjust OWL's configuration for different observing goals is a valuable capability, and care has been taken to assure that the OWL satellites have sufficient fuel and maneuverability to make these changes.*

The OWL mission will end when scientists command both OWL satellites to undergo controlled re-entry to the atmosphere, so as to minimize any risk from re-entering debris.

The NIGHTGLOW experiment in Alice Springs, Australia, prepares for a launch beneath a balloon that will lift the instrument above 99% of the atmosphere to measure ultraviolet light reflected by the Earth at night. Photo courtesy of the NIGHTGLOW team.

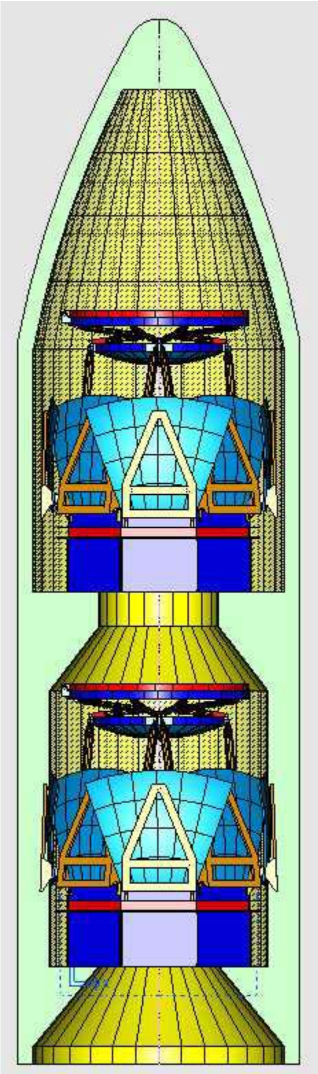
The Future Has Begun

OWL scientists have already begun gathering the background scientific data needed for the mission. The NIGHTGLOW balloon experiment is designed to spend evenings floating in the stratosphere detecting naturally-occurring, background UV radiation produced by a variety of sources -- including moonlight and starlight, the interaction of oxygen and nitrogen molecules in the atmosphere, human-made lighting, and even the bioluminescence of squid and other animals. NIGHTGLOW has had a test balloon flight, and is scheduled for a multi-day around-the-world flight, providing the baseline data on background UV fluorescence so that OWL can distinguish this light from that created by UHECRs.

The late David Schramm of the University of Chicago once commented how exciting the search is for ultrahigh-energy cosmic rays when even the most mundane of explanations involves a supermassive black hole. Across the globe, nature is literally pelting us with these cosmic messengers every day at every hour. This is no daydreamer's endeavor. OWL can cast a large enough net to catch these enigmatic cosmic rays, and *technology exists to build OWL today*. The design is both simple and elegant. Yet the rewards may be the stuff daydreams are made of: insights into black holes, extra-dimensions, folds in spacetime, newly discovered particles, and the nature of gravity itself.

The field of cosmic rays is no stranger to cutting-edge physics. The study of cosmic rays led to the discovery of antimatter, muons and neutrinos, all once in the realm of daydreams. Opportunity knocks once again. Mysterious particles traveling from beyond our Milky Way galaxy at essentially light speed call to us. It's time we answered the call.

Mission Specs



Mission:

* Launch vehicle: Delta IV
* Two formation-flying satellites
* (600 km nominal satellite separation is variable)
* Near-equatorial orbit (5 - 10° inclination)
* 1,000 km altitude (550 km at end-of-mission)
* 3-year mission lifetime
* 2×10^6 km^2-sr instantaneous aperture

Focal Plane:

* 2.3 meter diameter focal plane
* Formed by mosaic of multi-channel elements
* Commercial technology (flat panel photomultiplier)
* ~ 539,000 total channels
* Switched capacitor array ring buffer/readout
* 1 - 10 msec readout time
* 10^{-3} - 10^{-2} dead time fraction
* Focal plane detector and electronics power < 1000 W

Optics:

* f/1 System
* 300 - 400 nm wavelength range
* Transmission: 43% (on-axis, 0°) - 62% (off-axis, 22.5°)
* Spot-size (RMS): 1.03 mm (on-axis, 0°) -0.98 mm (off-axis, 22.5°)
* 3.0 meter diameter optical aperture
* 7.1 meter diameter aspherical mirror
* 2.3 meter diameter focal plane
* Full FOV 45°
* 3 mm focal plane pixel diameter
* ~ 1 mm, 0.1° alignment tolerance

For more information, refer to http://owl.gsfc.nasa.gov
The booklet was written and prepared by the OWL team.

"For the first time in a quarter-century, experiment is driving theory at the frontier, and not the other way around… Our telescopes become detectors in the greatest high-energy physics laboratory in nature, to observe the traces of the most awesome high-energy events of all time…"

John Marburger
Director of the U.S. Office of Science and Technology Policy
SLAC, October 2002

"[Ultrahigh-energy cosmic rays] is a remarkable field in which the most conservative explanation involves supermassive black holes."

David Schramm
November 1997

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