Dear Friends,

In my last letter, I mentioned that we were concluding a search for a new assistant professor, and I promised to update you. Dr. Alex Hayes, a 2011 Caltech PhD and Cornell graduate (B.A. 2003 in Astronomy, M.Eng. 2003 in Applied and Engineering Physics) will join the faculty beginning January, 2013. Alex is a brilliant young scientist whose current focus is the methane lakes on Titan. He will join us after completing a distinguished fellowship at the Miller Institute in Berkeley. We are looking forward to Alex’s return to Ithaca eagerly!

Very Dear Friends

Some twenty years ago many of us together formed the family of the Friends of Astronomy at Cornell and we have had a close relationship ever since. Most every year we have had Friends Symposia and other gatherings and we have kept in contact with numerous messages. Ten years ago Patricia Fernández de Castro began the now famous Orion Newsletters.

The Second Annual Yervant Terzian Lecture

Located south of Orion’s Belt, the Orion Nebula is approximately 1,300 light years away and has a diameter of about 24 light years. The star forming region’s glowing gas clouds and hot young stars are on the right, while the smaller nebula M43 is near the center and the dusty, bluish reflection nebulae NGC 1977 and friends on the left. Within this stellar nursery, astronomers have also identified what appear to be numerous infant planetary systems.

Credit & Copyright: Jesús Vargas (Astrogades) & Maritxu Poyal (Maritxu)

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Winter 2011

Very Dear Friends of Astronomy

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P. Fernández de Castro, Editor
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On Wednesday, November 9, 2011, Dr. Mario Livio, of the Space Telescope Institute, delivered the second annual Yervant Terzian Lecture that Chuck Mund Jr. endowed two years ago. The title of his talk was the *Top Scientific Achievements of the Hubble Space Telescope*. Dr. Livio, who is the author of *The Golden Ratio* and other books, delighted the audience with an hour-long discussion of major astrophysical breakthroughs that the Hubble has made possible, each one illustrated with stunning images.

Among the discoveries he highlighted so beautifully were:

- The accelerating Universe, dark energy and dark matter;
- The distance scale and the age of the Universe;
- Evolution of galaxies and the cosmic star formation rate;
- Extrasolar planets and the search for planets in the Galactic Bulge;
- Supermassive black holes in the centers of galaxies;
- Gamma ray bursts;
- Stellar populations in nearby galaxies;
- Galaxy collisions;
- Birth of stars and planets;
- The impact of comet Shoemaker-Levy 9 on Jupiter;
- Stellar life and death;
- and

When he discussed galaxy collisions, the birth of stars and planets and stellar life and death, Dr. Livio added to the gorgeous Hubble pictures remarkable simulations that combined Hubble photos and computer generated imagery that gave us an impressive 3D experience of the Universe.

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**Very Dear Friends (cont.)**

that have added an important ingredient to our group. From the beginning I acted as the Faculty Liaison with the Friends and it is now time to pass this honor to another faculty member in this evolving Department of ours. I am happy that Professor Martha Haynes will succeed me in this most enjoyable role. She will be in touch with you shortly. Patricia will remain as your primary contact and editor of the *Orion*. I, of course, will continue to participate in Friends activities. I would not miss them for anything!

It has been an honor to work with you, as I have treasured your friendship through the years. I will always be your friend and you can get in touch with me anytime you wish. I would also like to thank you for the generosity you have shown to our Department through the years.

Hoping to see you here at our next Symposium!

Yervant

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**Dear Friends**

The Department is presently conducting another search for a new assistant professor, this one to work in one of the many areas of astronomy that will be probed by the CCAT telescope. The search committee has just begun to review the applications; as of today (11/3/11), we have 109 applicants for this position, so we have a lot of reading to do, much less the even more challenging job of ranking the applicants. I hope to report to you on a successful hire in the next newsletter.

Another piece of news that will no doubt be bittersweet for many of you: Yervant Terzian is stepping down from his role as the faculty leader of the Friends of Astronomy. But fear not: not only is Yervant not deserting you, but we also have found a wonderful person to replace him in this vital role, Martha Haynes. And Patricia will continue her administration of all things related to the group, including *Orion*.

Finally, you will read with pleasure the article in this edition of *Orion* written by Bob Cowie and Yervant on the history of the Friends of Astronomy group. Next May, we are planning a gala celebration of the 20th anniversary of the formation of the Friends. We hope everyone will be able to attend—details will be sent to you in January.

Best wishes for the holidays, and Happy New Year,

Ira
Soon the Friends of Astronomy will celebrate its 20th birthday as an organization. The idea for the Friends was born during a Cornell Adult University trip in 1992 to southern Arizona led by Yervant Terzian and Verne Rockcastle. Verne was then a professor of Education in the Ag School Department of Natural Resources. While Verne held the participants rapt, as only he could, with a lecture on the Mud Dauber Wasp as we all crouched over a mud puddle, the highlights of the trip for many of us were a visit to the mirror laboratory at the University of Arizona, where Roger Angel had developed and was using a new technique for casting very large parabolic mirrors for use in astronomic telescopes, and an afternoon-evening visit to Kitt Peak, the National Optical Astronomy Observatory. There many of us saw for the first time the planet Mercury and realized that the planet Venus had phases just like Earth’s moon. It was an exciting and intellectually gratifying trip.

We met for the first time on that trip, and then began a friendship that has grown warmer and deeper over the intervening years. In the course of our many conversations while we were in Arizona, it became clear to us that there were many intelligent adults who were very much interested in astronomy and the myriad mysteries of this wondrous universe and our life and existence in it, that astronomers were probing every day. Why not offer them an opportunity to interact on a more regular basis with one of top-ranked astronomy departments in the world? Yervant charged Bob with writing a proposal, which he soon did. Thus was born the Friends. It was to be a loose organization, with no requirements for membership beyond an interest in astronomy and a desire to connect with the Astronomy Department. There would be no dues, and the Friends would not be primarily a fund-raising group, but we realized that connection often leads to increased interest and involvement, and that these two things often lead to financial support as opportunities to thoughtfully further the work of the department emerge in the natural course of affiliation. This we would most certainly encourage.

The first Friends were invited to membership using lists of former participants in Yervant’s CAU classes, others known to have an interest in astronomy, and recommendations from the Dean of Arts & Science, about 120 names in all.

The Department of Astronomy picked up the ball and ran with it. The first Friends of Astronomy Symposium took place in the Fall of 1992. Some 75 Friends participated and it was an outstanding success. Over the course of the intervening years, Friends have been treated to a galaxy (sorry!) of exciting and unique opportunities to learn more about the universe in which we live and the scientific efforts to understand it. Symposia for the Friends, often in connection with other events sponsored by the Department of Astronomy, have been held almost every year since the founding. Among the most exciting of these was the symposium held May, 1999 in honor of Yervant’s 60th birthday and in special recognition of his 20 years of service as head of the Department, a position he would relinquish on June 30 of that year, setting a record for the College of Arts and Sciences for longest tenure as chair. On that very special occasion, the Friends announced the creation of the Yervant Terzian Scholarship Fund for astronomy majors, or physics majors interested in astronomy, supported by almost $446,000 in gifts from the Friends.

Other exciting events included a special invitation to the Friends to attend the launch at the Kennedy Space Center of the Contour Mission to explore asteroids. Joe Veverka, who was Department Chair at the time, was the principal investigator on this mission. The launch itself was spectacular and the talks preceding it excellent. Sadly, however, the mission was ill-fated as the space craft exploded for reasons unknown a short time later while it was in solar orbit awaiting injection into its mission trajectory. In the Fall of 2008 the Friends were the special guests of the American Astronomical Society’s Division of Planetary Sciences as that international group of eminent planetary scientists met in Ithaca.
Not every meeting has been confined strictly to the discussion of scientific topics. One meeting in particular was highlighted by the introduction of a rap song written and composed by one of our very creative members and dedicated to all astronomers everywhere. Space limitations prohibit recreating the entire seven very clever verses here, but the refrain itself gives the feel of the whole:

Oh yeah, in space and time
The Big Bang is the paradigm.
No way will it be wrong
‘til something better comes along.

Allegedly this number topped the charts a short time. Thank you, Barbara. A great time was had by all as the dragooned chorus of Friends rendered this for the gathering.

While we mentioned earlier that the Friends was not organized as a fund raising group, no history of the Friends would be complete without some recognition of the very substantial financial support which the members of the Friends have provided for the Department of Astronomy. Here is a (perhaps only partial) list:

- Bryan and Kathleen Patten Graduate Fellowship in Astronomy
- Bryan and Kathleen Patten Graduate Teaching Assistantship in Astronomy
- Kenneth A. Wallace Professorship in Astronomy
- Ed Leister Student Fellowship Award
- Bob Ohaus Student Fellowship Fund
- Yervant Terzian Undergraduate Scholarship Fund, endowed by a group of Friends
- Dan and Betty Roberts Undergraduate Scholarships
- Ed Hewitt Computational and Visualization Undergraduate Center
- Bob and Vanne Cowie Arecibo Meteorite Collection
- Twelve Arecibo Auditorium Chairs
- E. E. Salpeter Visiting Professorship, endowed by a group of Friends
- The Cranson W. and Edna B. Shelley Graduate Student Research Awards
- The Cranson W. and Edna B. Shelley Undergraduate Student Research Awards
- The Cranson W. and Edna B. Shelley Teaching Assistantship Awards (the last three established by Vanne and Bob Cowie)
The Charles and Barbara Burger Special Colloquium Series, endowed by Chuck and Barbara Burger
The Josephine Lawrence Hopkins Foundation Colloquium, endowed by the Hopkins Foundation thanks to the efforts of Lee and Nancy Corbin
The Maryanne Shelley Jessup MacConochie Colloquium, endowed by Vanne and Bob Cowie
Numerous gifts to the Palomar Project
The Josephine Hopkins Radio Telescope at the Space Sciences Building, arranged by Lee and Nancy Corbin
Fred Young’s eleven million dollar gift to support the Atacama Telescope Project (CCAT)
The Celebrating Yervant dvd, produced by Phil and Maddy Handler and distributed by Chuck and Carol Mund
The Yervant Terzian Endowed Lectureship, established by Chuck Mund jr.
The Josephine Hopkins annual summer undergraduate research awards and colloquia, sponsored by Lee and Nancy Corbin
Numerous Annual Gifts

Clearly, the support of the Friends has been exemplary and continuous, and we thank each of our many donors for their very generous support. They have made a very real difference in the life of the Department and its ability to carry out its mission of teaching and research.

One of the real benefits or membership in the Friends has been the receipt of our (semi-annual) newsletter, The Orion, capably edited by Patricia Fernandez de Castro, Yervant’s beloved wife. This publication, one edition of which you now hold, carries articles on the latest research efforts within the Department as well as comments on contemporary topics in astronomy and a lively question and answer section.

Twenty years later, the Friends is as enthusiastic as ever. Though Yervant will continue to be a Friend and a friend to all the members of the group, next year the responsibility of leading it will pass on to the shoulders of the wise and vivacious Professor Martha Haynes, with whom we will continue our exploration of the wonders of our universe. To celebrate the twentieth anniversary of the Friends of Astronomy, we will have another glorious symposium. We hope we’ll see all of you then!

Bob Cowie and Yervant Terzian
Few people are impressed by dust; from a dynamicist’s point of view, however, it is extremely interesting due to its mobility. The fact is that gravity tends to keep objects in orbit where they are. For example, a basketball-sized chunk of debris generated by the irregular satellites will remain there in orbit. Dust, however, is small enough to be affected by light striking it from the Sun. As a consequence, the orbits of dust particles slowly decay inward toward the planet. This was the missing piece that Steven Soter, then a research associate at Cornell, found in 1974. He hypothesized that as this dark cloud of dust migrated inward from the irregular satellites, it eventually reached the orbit of Iapetus, the outermost regular satellite. Moving along its orbit, the initially bright Iapetus plowed through this dark cloud thought to be remnants of the planet formation era that were subsequently captured into orbit by the giant planets’ gravity. As a result of this essentially random process, the irregular-satellite’s orbits are haphazardly oriented and frequently cross one another, as the figure on next page shows. This leads to the unavoidable conclusion that such objects must have suffered a violent history of mutual collisions over the course of the Solar System’s history. To add insult to injury, their surfaces have also been continually bombarded by interplanetary micrometeoroids crashing in at over ten thousand miles per hour. The result is that far from Saturn, the irregular satellites must have generated a vast swarm of dark debris and dust.

Observing the Saturnian system in 1671, the Italian-born astronomer Giovanni Cassini discovered Iapetus—perhaps the most enigmatic moon in the Solar System. Following the discovery, Cassini was perplexed to find that in subsequent attempts to locate the satellite, it was only visible at points in its orbit when it lay to the West of Saturn, not when it lay to the East. Only thirty-four years later, with improved telescopes, was he able to detect it where he had not managed before. Shockingly, from one side of its orbit to the other, Iapetus dimmed ten-fold!

From this scant information, Cassini surmised that one face must be ten times darker than the other. He also pointed out that this explanation required that Iapetus, like our Moon, be tidally locked to its host planet. Just as the near side of the Moon always points toward Earth, Iapetus would keep the same face pointed toward Saturn. The figure below depicts the view of this configuration from the Earth. On one side of Saturn, Iapetus would move toward the Earth in its orbit, revealing its dark leading side. Half an orbit later, the brighter trailing side would be exposed.

This was a bold claim. No other known body in the Solar System exhibits such a dichotomy. It is fitting, therefore, that over three hundred years later, it was the spacecraft named in Cassini’s honor that arrived at Saturn, sailed by Iapetus, and provided the sharpest images to date vindicating Cassini’s daring hypothesis.

But what could cause such a stark contrast? Cassini could not answer this question, and the explanation had to wait a further three hundred years. The key lay far beyond Iapetus, with an odd population of dark moons at the outer reaches of Saturn’s gravitational influence—the irregular satellites.

As opposed to the brighter regular satellites that were assembled close in at the same time the planet itself was forming, the dark irregulars are thought to be remnants of the planet formation era that were subsequently captured into orbit by the giant planets’ gravity. As a result of this essentially random process, the irregular-satellite’s orbits are haphazardly oriented and frequently cross one another, as the figure on next page shows. This leads to the unavoidable conclusion that such objects must have suffered a violent history of mutual collisions over the course of the Solar System’s history. To add insult to injury, their surfaces have also been continually bombarded by interplanetary micrometeoroids crashing in at over ten thousand miles per hour. The result is that far from Saturn, the irregular satellites must have generated a vast swarm of dark debris and dust.

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As opposed to the brighter regular satellites that were assembled close in at the same time the planet itself was forming, the dark irregulars
material. In the process its leading side became darker.

Where do I fit into this picture? My advisor Joe Burns, who was a member of Steven Soter’s thesis committee, has been interested in and tackled this problem since the beginning. He proposed it as a project for me when I first arrived at Cornell. Despite the idea being suggested 35 years ago, no one had done a full quantitative investigation taking all the effects into account.

We found that the vast majority of the dust mass strikes Iapetus, with a small fraction slipping by and impacting the next two satellites, Hyperion and Titan. Furthermore, it turns out Iapetus is not exactly half bright and half dark—the dark material actually extends onto the trailing side along the equator, somewhat like the lines on a tennis ball. By calculating where dust particles would land on the surface, I was also able to match the observed pattern as a natural consequence of the dust particles moving on elliptical rather than circular orbits.

And the timing could not have been better. At the first conference I presented our results, a group using the Spitzer infrared telescope announced the discovery of a vast ring of dust originating from the Saturnian irregular satellites. The dust had been caught in the act! This spurred much interest in the community, and the amount of dust observed allowed us to make quantitative estimates of how much material would accumulate on Iapetus. The combination of observations and our theoretical calculations make a powerful case that Soter’s mechanism is correct.

But why stop at the Saturnian system? All four of the giant planets host large numbers of irregular satellites and should undergo the same irrevocable transfer of dark material from their outer reaches onto the brighter regular satellites further in. Prof. Burns and I have also investigated these others, and found a big surprise along the way at the planet Uranus. Uranus is unique in the Solar System in that it is tilted almost completely on its side as it orbits the Sun. It turns out that the complex interaction between this fact and the gravitational tugs dust particles feel from the Sun’s gravity as they move about Uranus causes their orbits to become chaotically unstable as they evolve inward. This should splash dust throughout the inner Uranian system. This contrasts with the other planets where the one or two large outer regular satellites intercept the vast majority of the material.

Images of Iapetus’ contrasting faces taken by the Cassini spacecraft during a targeted fly-by. The dark leading side is to the left. To the right is a slightly angled image of the trailing side, with dark material extending into it along the equator. The ten-fold brightness difference between hemispheres is unique in the Solar System.

Photo: NASA/JPL/Space Science Institute.

It is also important to point out that our observational knowledge of this process is currently quite patchy. The dust itself has only been observed in the Saturnian system, at a single wavelength. We therefore entered a proposal to use Herschel, the newest and currently most powerful infrared space telescope. We proposed to investigate the Saturnian ring at new wavelengths, as well as to search for analogous rings at Uranus and Neptune. Excitingly, the proposal was accepted, and we are currently busy analyzing the first set of data received from Saturn. What secrets lie waiting in the data? We will have to wait and see! Surely we will yet encounter many new surprises as we continue to piece together the strange puzzle Cassini posed over three hundred years ago.

-Daniel Tamayo
What happens when a black hole collides with another black hole or a neutron star? In order to find out, I, along with the numerical relativity group at Cornell and collaborators at the California Institute of Technology, the Canadian Institute of Theoretical Astrophysics, and Washington State University, have developed a large computer code to run simulations on supercomputers.

The reason we use these simulations to study black holes has to do with their strong gravitational fields. Einstein’s theory of general relativity is our current best description of how gravity works. This theory replaced Newton’s laws of gravity, which are a good approximation when objects move slowly and one is not near the surface of a black hole or a neutron star. Newton’s laws of gravity can adequately explain gravity on Earth and in our solar system unless very precise measurements are made, and even then we can use easily computed corrections to Newton’s theory (called a post-Newtonian approximation to general relativity). Near neutron stars and black holes, however, gravity is very, very strong. However, in this strong-field regime, the equations describing gravity are so complicated that the only way we can solve them is by doing large computer simulations, which allow us to formulate predictions based on general relativity and then test them.

Neutron stars are stellar objects with matter at super-nuclear densities that cannot be produced in the laboratory. Their mass is about that of 1.5 to 3 solar masses, but compressed into an object the size of lower Manhattan. Black holes are objects so dense that nothing, not even light, can escape from within their surface, which is known as the event horizon. Black holes can range in size from stellar masses (about 3-100 solar masses) to supermassive black holes (millions to billions solar masses), which are found at the centers of galaxies. Neutron stars and stellar mass black holes are born when normal stars die. When a star of at least 8 solar masses has exhausted most of its nuclear fuel, its core collapses, leading to a massive explosion known as a supernova. Most of the star is ejected in the explosion, but the core continues to collapse into either a neutron star or a black hole, depending upon its mass and composition. Generally, stars in the range of 8-25 solar masses will form neutron stars.

Black holes, like any other astrophysical objects, can collide with each other or with other astrophysical objects. Collisions with other black holes or with neutron stars primarily occur in binary star systems where both stars have died to form either black holes or neutron stars and the less massive object spirals/is attracted into the gravitational field of the more massive one. Alternatively, these binary systems can be formed when two of these objects are in, or come into, close proximity and fall into each other’s gravitational field in the denser central regions of galaxies or when two galaxies collide. The result of these collisions of stellar mass black holes is the formation of supermassive black holes.

1 Professor Saul Teukolsky, Research Associates Geoffrey Lovelace, Rob Owen, and Mike Boyle, and graduate students Dan Hemberger, Curran Muhlberger, Andy Bohn, Francois Hebert, and Will Throwe.
Since black holes don’t emit any light, how can we observe them, either singly or colliding? One possibility is by detecting gravitational waves. Gravitational waves are ripples in the fabric of spacetime that travel unimpeded across the universe at the speed of light. They are produced in almost any place in which masses are accelerated, such as two heavenly bodies orbiting about each other in a binary system, or in a supernova explosion. Gravitational waves are very weak, however, so only massive bodies like stars and black holes can produce waves strong enough to be detected. For a binary system, the strength of the waves is greater the more massive the bodies, the closer together they are, and the faster that they orbit about each other. As the binary system emits gravitational waves, energy is carried away by the waves, and this causes the orbit to shrink so that the two bodies slowly inspiral toward each other and eventually collide. As the strength of the wave falls off with the distance from the source, it takes stellar mass objects orbiting about each other hundreds of times per second to produce gravitational waves that we have any hope of observing using ground-based detectors. And this is only possible in binary systems containing black holes and neutron stars, as ordinary stars would be shredded by tidal forces before they could get close enough together. In other words, detecting gravitational waves is one of the best ways to detect black holes and, conversely, currently we can only hope to detect gravitational waves from binary systems formed by two black holes, two neutron stars or one of each.

When a gravitational wave passes by the Earth, it causes the distance between two objects on our planet to alternately stretch and shrink. Several L-shaped gravitational-wave observatories, such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) have been built in the past decade. Their detectors monitor the lengths of their 4 km long arms looking for one arm to shrink and the other to stretch by a distance smaller than an atomic nucleus. So far they have not directly observed any gravitational waves, but at their current sensitivity, they would have been lucky to do so. These detectors are currently undergoing upgrades which will increase their sensitivity by a factor of ten, allowing them to detect gravitational waves from a volume of the universe a thousand times larger than before. Estimating how often a compact binary system will merge in a given volume of the universe is a complex problem with large uncertainties, but the expected

To think about gravitational waves, it is helpful to compare them to water waves. If a water wave passes a ship in the ocean broadside, we will see it raise and drop. In contrast, if a gravitational wave passed in the same direction, we would see it grow taller, then shorter.

On water, the amplitude, or size of a wave—the height of its peak or the depth of its trough, measured relative to its center—is the distance the ship moves up or down from its center position. For the gravitational wave, it is the percentage of squeeze or stretch by which the wave distorts the ship.


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2 For more on LIGO, please see <http://www.ligo.caltech.edu/>.
rate of observable events should increase from one every 50 years to one a week after the upgrades are completed in 2015.

The exact size and frequency of gravitational waves depends upon the masses and spins of the black holes and neutron stars that give them birth. Ground-based gravitational wave observatories are sensitive to waves that pass by tens to hundreds of times per second. Gravitational waves such as these are only produced by the final dozens to thousands of orbits of stellar-mass binaries and their subsequent mergers. When the two bodies are far apart, a post-Newtonian approximation can be used to predict the waveforms. During the late stages of inspiral (the last dozens of orbits) and the merger, however, this approximation breaks down, and Einstein’s equations can only be solved numerically using computer simulations. As the gravitational waves detected by ground-based observatories are expected to have a weak signal, it is important to have an accurate prediction of what they look like, so they can be extracted from a “noisy” detector (i.e., much as when you are trying to listen to a very faint radio station, it helps to know the song that is being played). This is done by generating a large template bank of possible signals (which depend upon the masses and spins of the bodies in the binary) and comparing them with the output of the detector. In order to learn as much as possible from the gravitational waves, the template bank needs to have about a million waveforms corresponding to the different possible physical parameters of the binary system. Since it is prohibitively expensive to carry out that many simulations (each simulation takes over a month), we need to build an analytic model waveform that is calibrated by as many simulations as we can do. It is the goal of our group to carry out these simulations.

As solving Einstein’s equations on a computer is very complex, it has taken us ten years to write and develop the techniques in our 300,000 line code. Our code is currently the most accurate and efficient in the world for simulating the late inspiral and merger of two black holes. It allows us to do hundreds of simulations a year in order to calibrate analytic models that can be used in searches for gravitational waves from collisions of black holes.

So what happens when two black holes collide? They form a larger distorted black hole that after some additional gravitational radiation eventually settles down into a black hole with a mass roughly equal to the sum of the masses of the original two black holes. Our simulations also predict the gravitational waves emitted during this process. In the near future, once detections begin, we hope to iterate back and forth between observations of gravitational waves and the predictions of our simulations in order to learn if Einstein was right about black holes.

We will also test the models that predict the distribution of black hole binaries throughout the universe. To learn more about our simulations, and see movies of them, please visit <http://www.black-holes.org>.

What happens when a black hole and neutron star collide? The fate of the neutron star primarily depends upon the relative sizes of the black hole and neutron star, the spin of the black hole, and the (currently unknown) properties of nuclear matter at the extreme densities found in a neutron star. If the black hole is much larger than the neutron star, the neutron star simply falls into the black hole. For more comparable masses, however, the neutron star may be ripped apart by the black hole. In this case, most of the matter falls into the black hole, but some may be ejected away from the black hole, and some may stay and form a disk (like the rings of Saturn) around the black hole. When the neutron star is torn apart, the gravitational wave signal drops suddenly.

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3 Future space-based gravitational detectors will be sensitive to gravitational waves of lower frequency (waves every few minutes) which are produced during the final orbits of supermassive black holes.

4 Recall that a post-Newtonian approximation is an easily computed correction to Newton’s laws of gravity that is valid when objects move slowly and one is not near the surface of a neutron star or black hole. Thus until the two bodies get very close together, it will be a good prediction of how the bodies orbit about each other, and the gravitational waves produced.
By studying when this happens, we can learn something about the structure of neutron star matter. The possible formation of a disk is very exciting, as it may provide the engine for what is known as a short gamma-ray burst, an extreme explosion of light that can be seen across the universe. Satellites currently detect many of these gamma-ray bursts and collisions of two neutron stars or a neutron star and a black hole are believed to be one of the primary sources of these bursts. It will be very exciting if we are able to simultaneously detect both the gravitational waves and the gamma-ray burst from such a system!

-Larry Kidder

Two simulations of a black hole colliding with a neutron star seven times less massive. The difference between the two is the spin (how fast it is rotating and dragging matter in, like a whirlpool). On the right, the spin is about twice as much as on the left. On the left, the flattened circle is the black hole’s horizon. On the right, it is the edge of the white circle. The grey and black regions depict the density of the neutron star’s matter. On the left, the black hole pulls the star into an elongated shape as the neutron star plunges into the hole, but does not fully tear it apart. On the right, the star was fully torn apart before reaching the hole’s horizon, and about 30 percent of its mass has been strung out into an ultrahot, ultradense “accretion disk” that encircles the hole. As it forms, this disk should emit gamma rays and neutrinos, as well as gravitational waves.

Image: Francois Foucart (Cornell, CITA).

Stellar-mass black holes can grow by pulling gas off a companion star that orbits around it, as depicted in this artist’s impression. By a series of such accretion events and collisions with each other, a large number of stellar mass black holes can gradually grow into a supermassive black hole.

In 185 AD, Chinese astronomers recorded the appearance of a new star in Alpha and Beta Centauri. RCW 86 is thought to be a Type la supernova such as the ones discussed in the science talk by our second Yervant Terzian lecturer, Mario Livio, a white dwarf star that exploded as it accreted material from a companion in a binary system. Like SN 1987A, about which Ira Wasserman writes staring on page 12, RCW 86 would have emitted neutrinos when it exploded.

Photo: XMM-Newton (X-ray), Chandra / WISE, Spitzer (IR).
Q. How likely is it that neutrinos may exceed the speed of light, as shown in the results of the recent CERN experiment? And if so, what does this mean for Einstein’s Theory of General Relativity, in which nothing can exceed the speed of light, and for our understanding of space-time?
A. What is the sound of one hand clapping? This cliche is a key to understanding why any experiment to measure the speed of neutrinos is so challenging.

Ideally, to measure the speed of a particle, you observe it passing some point at some time, then observe it at a later time passing some other point a known distance away. The speed is the distance travelled divided by the time between the two observations.

To give an example, suppose a car leaves a garage at 12 noon, and its departure is recorded by a security camera. It then drives 60 miles to a second garage, where it arrives at 1 PM, once again recorded by a security camera. From this we can conclude that the car drove at 60 mph between the two garages.

But now suppose that the security camera was not on when the car left the first garage, so we have no record of its departure; all we know for sure is that it arrived 60 miles away at 1 PM.

If that is all we know, we can say nothing about its speed. However, let’s suppose that we do know that the door to the first garage is only open between 12 noon and 12:15 PM. Then the car must have left between these two times, so it must have travelled for a time no more than one hour and no less than 45 minutes. Since it travelled 60 miles, its speed must have been between 60 mph and 80 mph.

Determining the speed of a neutrino is like finding the speed of a car if all you know for sure is when it arrived at the distant garage.

The reason is that neutrinos are very difficult to detect. It may surprise you to learn that the Sun emits energy in the form of neutrinos at a rate comparable to the rate at which it emits energy in the form of light. But the neutrinos emitted by the Sun by and large pass right through the Earth. Quantitatively, on traversing the entire Earth perhaps one in a trillion solar neutrinos interacts with it.

Now imagine that you have a detector a lot smaller than the entire Earth. The probability of detection is roughly proportional to the linear size of the detector. So for a reasonably sized detector—say 10 meters across—perhaps one out of 100,000,000,000,000 neutrinos will be seen.

The numbers are slightly different for the OPERA experiment, since the neutrinos are more energetic than solar neutrinos, and hence interact a bit more strongly. That increases the probability of interaction significantly, perhaps by a factor of a thousand, but still only one out of 100,000,000,000,000 would be seen in a detector.

What is most important is that even if you see a neutrino in your detector, it is very very very very unlikely that you will see it again in another detector.

So now imagine that you “are sure” that neutrinos whose arrival times are recorded in a detector were all emitted by a source at a known distance away over some range of times. Now you can try to determine their average speed statistically.

To see how this might happen, let us return to cars and garages. Instead of one car, suppose two cars left the first garage and travelled to the garage 60 miles away at exactly the same speed. They are seen to arrive at the second garage at 1 PM and 1:05 PM. Since they travelled at the same speed, the car arriving at 1 PM must have left the garage at an earlier time than the one arriving at 1:05 PM. The first car must have left after the first garage door opened at 12 noon, so it travelled for at most an hour. Thus, its speed must have been at least 60 mph. The second car must have left before the first garage door closed at 12:15 PM, so it must have travelled for at least 50 minutes. Thus, its speed must be at most 72 mph. Thus, the speed of the cars must be between 60 and 72 mph. This range is smaller than we found before just from seeing one car: we get additional information from recording the arrival of the second car.

In a nutshell, this is how the OPERA experiment deduces the speed of neutrinos, except that their result is based on some 16,000
Neutrinos are subatomic elementary particles that were first postulated by Wolfgang Pauli in 1930 to explain the difference observed between the energy, momentum, and angular momentum of the initial and final particles in a particular form of radioactive decay called beta decay. Positing neutrinos enabled him to save the principle of energy conservation, which would have otherwise been violated. They were observed 20 years later emerging from nuclear reactors; today we know they are formed in the course of astrophysical events as supernova explosions and gamma ray bursts.

Physicists have established that neutrinos do not carry an electric charge. This means that they are not affected by the electromagnetic forces that act on charged particles such as electrons and protons. Thus, in the course of our lives, trillions of neutrinos from the sun go through each of us. Neutrinos are affected only by the weak subatomic force, which has a much shorter range than electromagnetism, and by gravity, which is relatively weak on the subatomic scale. This is why they able to travel great distances through matter without being affected by it.

There are three types, or “flavors”, of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos. Under certain circumstances, neutrinos can transit from one “flavor” to another as they propagate through space (“neutrino oscillations”). The OPERA experiment was designed to test this phenomenon, the appearance of tau neutrinos from a pure muon-neutrino beam propagated from Genève to Gran Sasso.

The OPERA detectors, which were completed in the summer of 2008, are composed of “walls” of “bricks” of photographic film. There are two targets, each with about 150,000 bricks arranged into parallel walls. Next to each target is a magnetic spectrometer, which measures the momentum and identifies the charge of the particles that penetrate the bricks as well as the location of the bricks where the neutrino interaction occurred.

Images: Istituto Nazionale di Fisica Nucleare, LNGS.
168,000 light years away, the speed of neutrinos must be at most a few hours divided by 168,000 years faster than that of light, or about a part in a billion faster. However, if the OPERA speed were correct, the neutrinos from SN 1987a should have been seen about 3.4 years before the light from the explosion—in late 1983! To their credit, the OPERA team mentioned the SN 1987a limit in their paper. They concluded that for both results to be right would require a speed of neutrinos that depends on their energy. As I am writing my third draft of this answer, there is another line of evidence that contradicts the OPERA result. A neutrino moving faster than light carries a little “extra energy” compared to a photon with identical momentum moving at the speed of light. That means that without violating the sacred principles of mechanics—conservation of energy and momentum—it can decay into a lower energy neutrino, also moving faster than light, plus particles. Andy Cohen and Sheldon Glashow of Boston University have shown that the neutrinos in the OPERA experiment could decay to a lower energy neutrino plus an electron and a positron, which ought to be detected in ICARUS, which is a companion experiment to OPERA. No such particle decays have been observed.

So, I do not believe that the OPERA result is correct, but it will turn out to be very hard to figure out what the mistake is. Some have pointed out that the claimed excess speed is of the same order as the orbital speed of GPS satellites, about $\frac{1}{77,000}$ times the speed of light. The implication is that the OPERA team made an error in using information from GPS to locate their source and detector. I would be surprised if such an elementary error were responsible for their result.

The nature of a statistical result like OPERA’s is that its precision is limited by the number of neutrinos detected. This necessarily introduces a subjective element: how significant must this result be to believe it? Because special relativity is supported by a huge number of experiments, most physicists would demand much higher significance than the OPERA team has reported. Unfortunately, to obtain such accuracy would take a ridiculously long time because it is so hard to detect neutrinos. When I say ridiculously long, I mean it—to improve the statistical accuracy by a factor of 100 (which would not convince me by the way) might take thousands of years, if not longer, unless far larger detectors are built.

If correct, the OPERA data could be consistent with relativity but not in three spatial dimensions. The mechanism is easier to visualize in fewer dimensions. Imagine that we live on the surface of a cylinder, a two dimensional surface, and that light rays are constrained to remain on that surface but neutrinos are not and so can move in the third, “extra” dimension. Then a neutrino emitted at some point on the cylinder and detected at some other point can travel through the interior of the cylinder, whereas a photon cannot. In going from one point to another, the neutrino takes a shorter path than the photon, and if both were emitted simultaneously, the neutrino would arrive sooner. Thus, even if the neutrino is constrained to travel slower than the speed of light, by taking a shortcut it can appear to travel faster than light from the

A pair of swallows doesn’t make spring ... nor do a few neutrinos, is the title of this photograph of the Gran Sasso d’Italia mountain, taken by physicist Luca Zappacosta. It is also a view shared by many physicists and astrophysicists around the world, including author Ira Wasserman.


Each of the about 150,000 bricks in the OPERA detectors weighs a little over 18 lbs. They are stacked to form parallel walls that are interleaved with lead sheets and plastic scintillator counters.

Photos: Istituto Nazionale di Fisica Nucleare, LNGS.
Books in Science and the Universe


The French called him “the most celebrated of all the astronomers of the Universe.” William Herschel was indeed a towering figure in the beginnings of modern astronomy. Of German descent, he and his younger sister Caroline lived most of their lives in England. He was born in 1738 and he died at the age of 83. William, though originally a musician (he composed more than 20 symphonies), is famous in history for his adventures in astronomy. He began as an amateur observer with small telescopes and eventually he became an eminent professional astronomer with membership in the Royal Society. In 1781 he discovered the planet Uranus and two of its moons. Working with his younger sister Caroline, an indispensable collaborator, William made surveys of the skies and catalogued hundreds of nebulae, clusters of stars and double stars.

Herschel excelled at building larger and better telescopes. During his life he manufactured some 60 reflector telescopes and used the best ones to make his observations. The largest one had a focal length of 40 feet and an aperture (mirror diameter) of about 50 inches, which made it, however, too huge and cumbersome to use.

In retrospect, one of his greatest discoveries was ‘infrared radiation’ from the sun, thus suggested that there must be an invisible form of light beyond the visible spectrum. The recently launched European Space Agency infrared space telescope is named ‘Herschel Space Observatory’ in honor of him and his sister Caroline.

-Yervant Terzian

Yervant’s Critical Thinking Corner

1) A tree doubled its height every day. It took one hundred days to reach its maximum height. How many days did it take to reach half its full height

2) Socrates arrives at a bridge that is guarded by Plato. He begs Plato to let him pass. Plato says, “If the next utterance you make is true, I shall let you pass, but if it is false, then I shall throw you in the water.”

Socrates replies, “You are going to throw me in the water.”

If Plato does not throw him in the water, then Socrates has spoken falsely and should be thrown in the water. But if he is thrown in the water then Socrates has spoken truly and should not be thrown in.

Socrates is surely frustrating Plato!

Barbara Asks!

(cont.)

viewpoint of experimentalists who only live and work on the two dimensional surface of the cylinder. However, this particular example could not reconcile OPERA with SN 1987a: the effect is purely geometrical, so there should be no energy dependence.

Theorists have examined the possibility that neutrinos can move in the extra dimensions allowed by string theory, whereas photons are forced to live in the three dimensions familiar to us. In these theories, neutrinos can appear to move faster than light from our three dimensional viewpoint. They do so by taking shortcuts through the additional dimensions of space in string theory.

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