Dr. Ojakangas grew up in Duluth, Minnesota, where he describes his youth as characterized by a deep fascination with nearly everything scientific. His early curiosity led him from one branch of science to another -- he kept a wide range of reptiles and amphibians (he had a tiger salamander and a pair of newts for over 12 years), and he collected carnivorous plants from the Minnesota swamps and mail-order. He had a chemistry laboratory in his basement, where he unsuccessfully (thankfully) tried to make nitroglycerin among other dangerous compounds, and he had a telescope with which he would sketch the positions of the moons of Jupiter on a nightly basis for months in succession. When he eventually discovered physics, he knew this was the perfect science for him.

Dr. Ojakangas' professional research has spanned a wide range of topics. He received his B.S. in physics and geology from the University of Minnesota at Duluth (UMD), where during his summers, he worked for Phillips Petroleum as a geophysicist, analyzing seismic data for purposes of petroleum prospecting. After graduating from UMD, he went on to obtain his M.S. in geophysics and his Ph.D. both from the California Institute of Technology.

Figure 1: Jupiter's moon Io seen from the New Horizons spacecraft while on its way to Pluto (NASA image).

Doctoral thesis: Coupled thermal and dynamical evolution of planetary bodies

Dr. Ojakangas' doctoral research, under the direction of professor D.J. Stevenson, resulted in three highly acclaimed papers, collectively referenced by over 430 other journal publications as of 2015. The first paper describes a mathematical model of the heat flow emanating from Jupiter's volcanically active moon Io (Figure 1) -- by far the most volcanically active body in the solar system, having turned itself inside out well over a dozen times during our solar system's history. The model predicts that Io may be volcanically active for nearly 10 million years, followed by quiescent periods lasting as much as 100 million years (Figure 2). This is due to a feedback mechanism acting between the thermal energy within Io and the energy stored in its orbit. As the orbit becomes more eccentric, energy is stored in the orbit, but tidal flexing and associated friction also increase, eventually leading to volcanic activity and collapse of the eccentricity. Then the process repeats. These complex dynamics, intimately tied to the remarkable Laplace Resonance involving Io, Europa and Ganymede, help explain the enormous amount of thermal energy presently being emitted from the surface of Io.

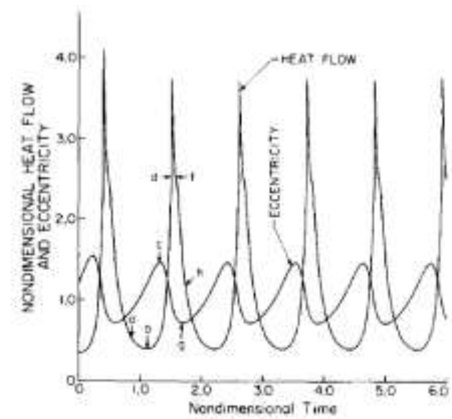

Figure 2: Orbital eccentricity (the "non-circularness" of Io's orbit) and surface heatflow are plotted versus time.

The second paper that resulted from Dr. Ojakangas' doctoral research describes the nature of the shell of water ice covering Jupiter's second large moon, Europa (Figure 3), which is covered with a complex network of global fractures. Due to global variations of solar radiation and internal tidal heating within this shell, this work showed that a vast ocean of liquid water should exist beneath the shell, decoupling its motion from the moon's rocky interior. This ocean has since been confirmed. Furthermore, the shell's thickness was predicted to vary in such a way that as it approaches thermal equilibrium, it may become dynamically unstable. Following on logically from these results, the third paper describes the dynamics of this shell as it is predicted to reorient itself by 90 degrees about the direction toward Jupiter. In the process of reorientation, it behaves like a pendulum falling from the top of its support to the bottom, while immersed in a viscous fluid. Such reorientation would create enormous stresses in the ice as the shell exhibits such polar wander. This process is predicted to repeat perhaps every 10 million years. Fracture patterns in Europa's ice, with the geometries expected from this phenomenon, were later discovered by analysis of spacecraft images.

Figure 3: Europa (NASA image).

While performing his doctoral thesis, Dr. Ojakangas had the privilege of searching for new asteroids with the world renowned astronomer and planetary scientist Gene Shoemaker and his wife Carolyn. Because of this stroke of good fortune, Ojakangas did in fact discover a new asteroid, and named it after his wife, Tracie. He had the wonderful experience of "giving" it to her as a Valentine’s Day present in 1986. This asteroid is forever named “3532 Tracie” by the International Astronomical Union, and is larger than the moons of Mars!

Post-doctoral research at the Lunar and Planetary Laboratory

Dr. Ojakangas performed his post-doctoral research at the Lunar and Planetary Laboratory of the University of Arizona, where he studied the formation of the solar system, and the closely related problem of planetary ring dynamics. Saturn’s rings are composed of an enormous number of ice balls (more than a mole of them!) and as such can be treated using statistical mechanics as with a gas of molecules – except that each “molecule” is a ball of ice, ranging from centimeters in diameter to the size of small moons. Alternatively, they may be treated with the equations of fluid mechanics. The differential equations employed in these methods are extremely challenging to solve and the solutions are difficult to understand. Dr. Ojakangas’ research expanded upon a qualitative idea conceived by his advisor, Dr. Richard Greenberg, which greatly simplifies the problem. Ojakangas placed this concept within a precise mathematical framework using a phase space comprised of (1) the tangential velocity of ring particles relative to a local circular orbit, (2) half of the radial velocity relative to the circular orbit, and (3) the radial position (Figure 4). In this coordinate system, ring particles constitute a continuum that circulates at constant angular velocity about the r-axis, while moving back and forth along it. Though much simpler, this approach reproduces many of the important results in planetary ring dynamics, such as the effective viscosity of such rings, and their tendency to spread radially, or form into ringlets.

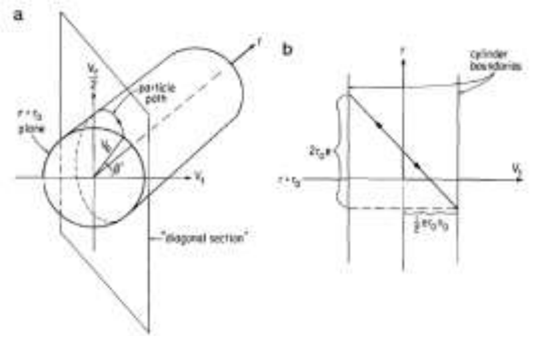

Figure 4: In the work of Ojakangas and Greenberg (1989), planetary ring particles are described in a novel phase space (see text) which simplifies the complex dynamics.

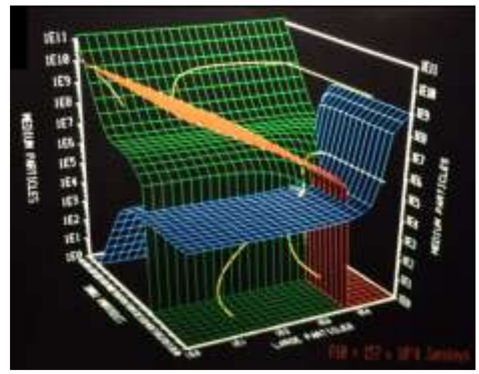

Figure 5: A simplified model of the orbital debris population with three object sizes, developed by Dr. Ojakangas for NASA.

Orbital Debris Research at the NASA Johnson Space Center:

Dr. Ojakangas went on to work at the NASA Johnson Space Center Orbital Debris Office in Houston for three years under then-director Donald Kessler (see Kessler Syndrome), where he was instrumental in the development of the latest computer models of the population of debris in orbit about the earth. Figure 5 shows results of a model developed by Ojakangas in order to describe the growth over time of three sizes of space debris objects – *large* (>1m), *medium* (10cm - 1m) and *small* (< 10cm). In this simplified model, the debris population evolves (yellow curves are examples) toward the point of intersection of the three surfaces shown. At one point, NASA officials were so impressed by the graphical depictions of space debris Ojakangas was routinely creating, that they framed some of them and gave them to the Chinese government on a diplomatic mission. One of these graphics is shown in figure 6, which depicts the catalogued debris from the explosion of a Chinese Long March rocket body while in orbit. Obviously, these gifts were given to the Chinese for more than their artistic value. Orbital debris is a growing problem that must be addressed by all space-faring nations.

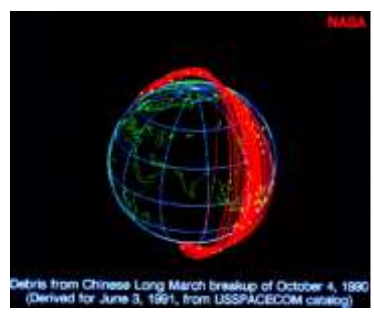

Figure 6: Depiction of catalogued debris objects from the explosion of a Chinese Long March rocket body.

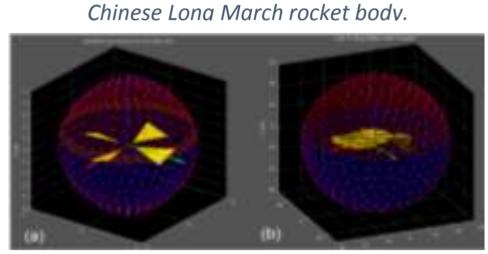

Figure 7: The solar radiation torque, theoretically computed for a synthetic pinwheel (left) and an actual piece of satellite debris (right).

Dr. Ojakangas has continued to work for NASA’s orbital debris program office as a consultant for over 20 years, and has been an author of numerous papers addressing many of the diverse aspects of the problem. Since 2009, this work has focused on understanding the rotation states of space debris objects, and how to determine these states using telescopic observations. In such observations, orbiting debris objects are seen as points of light that vary in intensity as they reflect sunlight toward an observer’s telescope. Rotation states of space debris are fascinatingly complex – for example, small objects can behave like wind vanes, spinning faster and faster as sunlight (acting like wind) hits them. Figure 7 depicts the solar radiation torque from all possible angles of incidence, acting on a synthetic pinwheel (left), and an actual debris object whose shape was measured using a laser scanner (right). Figure 8 shows some of the complex variations in orbital elements that occur as a result of the effects of solar radiation pressure.

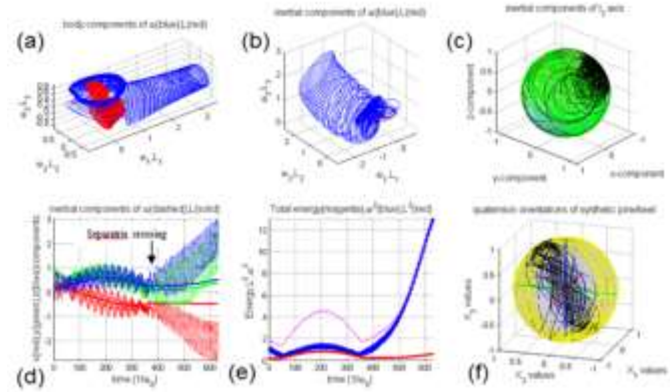

Figure 8: Orbital characteristics of a small debris object under the influence of solar radiation torque.

Figure 9 shows a prediction of the reflected light intensity over time, as a particular rocket body in [low-earth orbit]() is observed passing over a chosen observatory location. The object shown would be unresolvable in a typical telescope – only the variations in brightness (graphs) would be observed. Large debris of this kind are affected by eddy currents induced within them as they move through the earth's magnetic field, as well as internal friction and gravity gradient effects.

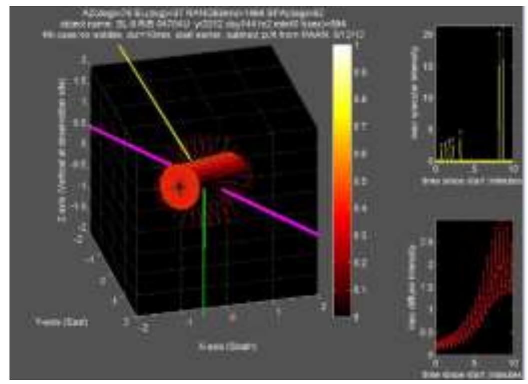
Figure 9: Specular (yellow) and diffuse (red) light curves seen by a telescope as rocket body passes overhead. Magenta, yellow, and green lines on image are rotation axis, direction toward sun, and toward observer. Click on image for video.

Experiments aboard NASA's weightless wonder aircraft:

Under the direction of Dr. Ojakangas, Drury University students have presented proposals accepted by the [NASA Reduced Gravity Student Flight Opportunities program]() seven times. Under this program, groups of students are given the chance to perform proposed experiments aboard NASA's Weightless Wonder aircraft, which simulates weightlessness by plummeting from 35000 to 25000 feet repeatedly over the Gulf of Mexico. Two of these experiments are described below.

The Orientation Ratchet:

Inspired by the way that a [cat turns when it falls]() (it is able to land on its feet while continuously maintaining zero net angular momentum) Dr. Ojakangas invented this robotic device, a variation of which could be used to turn satellites in outer space without the use of [propellant thrusters]() or [reaction wheels](). The robot was built by Drury University students Daniel Ratchford, Allison Harris, James Stockton, and Jeremy Woolery. There is a link [here]() at Drury University. The project originally garnered attention from around the world, including tech-news website Slashdot, Robot Haven, Space Daily and EE Times. The physics of its motion is described in this [document](), including its behavior when attached to a torsional pendulum (a long, strong section of fishing line). The project was submitted as a proposal to the [NASA Reduced Gravity Student Flight Opportunities Program](), and it flew on the [Weightless Wonder]() in the Spring of 2004.


Figure 11: Could this turtle turn itself, assuming it sits on a perfectly frictionless pivot? The answer is YES (if it were smart enough to understand how).

Click on the images below to see the device in motion, in normal gravity and on the [Weightless Wonder]() in microgravity.


Figure 12: Orientation ratchet on torsional pendulum under normal gravity.


Figure 13: Orientation ratchet operating in microgravity.

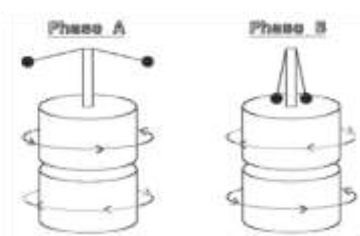

Figure 14: Diagram of orientation ratchet in its two phases of motion.

The Son of Toby robotic arm project:

Figure 15: diagram of two degree-of-freedom robotic arm, actuated by simulated muscles.

Soon after beginning to work on brain-machine interfaces (see below), Dr. Ojakangas felt compelled to build a robotic arm that is actuated by simulated muscles, in order to gain a better understanding of how neural impulses from the motor cortex in a human could activate numerous muscles to achieve the goal of a prescribed arm motion. The robotic arm, named "Son of Toby" after an actual human skeleton housed in the Drury University science division for over 100 years, has six muscles and two degrees of freedom (Figure 15). Two Drury University physics department teams flew versions of this arm on the Weightless Wonder aircraft, testing their ability to induce the arm's hand to trace out various planar trajectories in the absence of gravity. In developing this invention, the assistance of mechanical engineer Joshua Petitt was invaluable. By setting the acceleration due to gravity, g, either to 9.81 m/sec^2 or to zero, the arm successfully traced prescribed paths both in Drury's Muscle Systems Simulation Laboratory and on the aircraft.

Figure 16: Son of Toby robotic arm operating in microgravity. Click for video.

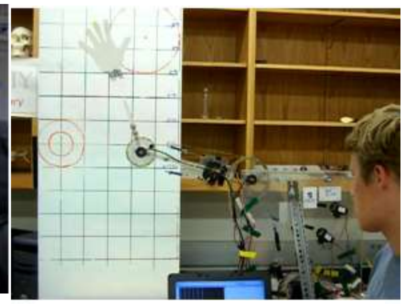

Figure 17: Son of Toby robotic arm operating in laboratory at Drury University.

Figure 18: The Drury University Holodeck.

A one degree-of-freedom arm with two muscles was built as an introductory experiment, and has been observed undergoing interesting chaotic motion when driven cyclically by its two muscles. A robotic arm with four degrees of freedom is also planned, but this currently only exists in the Drury University Holodeck.

Brain-machine interfaces

At the University of Chicago's Department of Organismal Biology and Anatomy, chips implanted in their motor corticies of rhesus monkeys record the discharge rates of over 100 neurons at a time, while the monkeys manipulate a robotic exoskeleton known as the KINARM (Figure 19), by Belkin Technologies. This machine records the positions of the monkey's shoulder and elbow joints, for the purpose of investigating the relationships between brain activity and arm motion. As shown in Figure 19, the KINARM has jointed sections in addition to those that directly correspond to the shoulder and elbow joints of the monkey. Dr. Ojakangas developed the equations of motion for the KINARM, relating torques applied at the shoulder and elbow joints by the monkey to the motion of the entire apparatus. For this contribution, Ojakangas is credited in the KINARM User's Manual.

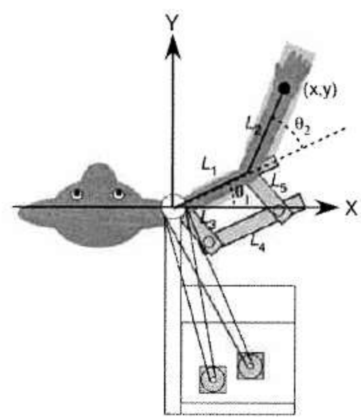

Figure 19: the KINARM by Belkin Technologies.

It was discovered over 10 years ago that the Cartesian position of a monkey's hand can be determined fairly well using a hyper-dimensional linear regression, using, as independent variables, the discharge rates of over 100 neurons and their histories over the one second prior to the time of the attempted prediction. This "brute force" methodology, completely lacking in the laws of physics, led Dr. Ojakangas and his colleagues to wonder whether a better fit would be attained by using the more physically reasonable assumption that neuronal discharge rates are proportional to muscle activation, and consequently, to torque generated at the shoulder and elbow of a monkey using the KINARM. This assumption was investigated, leading to this publication in the Journal of Neural Rehabilitation. Ironically, although this approach is almost certainly more closely related to the actual physics involved in arm motion, the fact that Newton's Laws of motion involve two time derivatives, each of which introduce noise to the system, led to a result that is only comparable to "brute force" model, rather than clearly superior to it. As of this writing, Dr. Ojakangas is working with a group of Drury students to test a new proposed model of his, relating activity in the motor cortex to the motion of the arm.

Rhythmic tidal deposits and stromatolites: clues to the ancient orbit of the moon

With an interest in both geology and astrophysics, Dr. Ojakangas has long been fascinated by a class of sedimentary rocks that hold clues to the ancient orbit of the moon. Under certain conditions, sediments deposited by tidal currents can record systematic variations in the heights of successive tides. These rocks, known as tidal rhythmites, record tidal cycles, such as the twice-monthly neap-spring cycle as well as others, as their successive layers varied in thickness due to the changes in the magnitudes of the tides and the tidal currents that supplied them. Working with his father, Emeritus professor of geology at the University of Minnesota Duluth, Ojakangas had the good fortune of discovering 1.85 billion–year-old tidal rhythmites in Northern Minnesota. Studying these sediments with high-resolution images of slabbed specimens, Ojakangas was able to extract information on the distance between the earth and the moon 1.85 billion years ago. This discovery constitutes some of the earth's oldest known tidal rhythmite deposits. Their research led to [this publication](#).

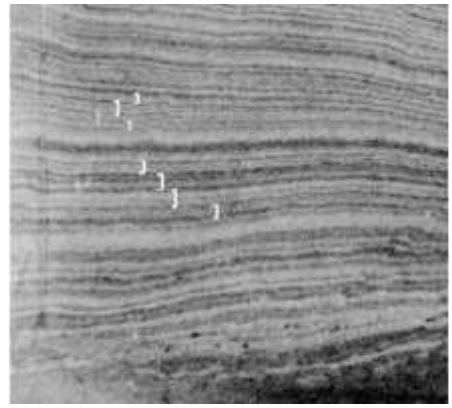

Figure 20: Daily pairs of layers (brackets) represent alternating semi-diurnal tidal events in the ancient Animikie Sea of northern Minnesota.

Stromatolite research:

For many years, Dr. Ojakangas has led classes of students in the analysis of some of the world's oldest fossils, while developing novel new models to explain how their shapes developed on the ancient earth. These peculiar fossils, known as stromatolites, are created as colonies of cyanobacteria grow and photosynthesize in shallow ocean water. They were the primary evidence of life for the first several billion years of life's history on our planet, but today only grow in a limited range of extreme environments where competition from more advanced lifeforms is absent. As the algae multiply, they cause calcite and other materials to precipitate on the growth surfaces, and sediment also may fall in from above. The one-celled bacteria therefore must grow through such materials in order to continue to receive sunlight, and in the process various shapes emerge, which are often preserved in the rock record. These shapes can vary widely, from thin, well-separated sinuous columns of centimeter diameters to broad, interconnected domed structures meters across. Because of the unparalleled span of time over which they formed, scientists have sought to use stromatolites to unlock ancient mysteries regarding the earth and the moon, such as the length of the day and the month, the latitude at which the structures grew, and the ancient obliquity (tilt) of the earth. With the help of colleagues, Ojakangas has extracted spectacular stromatolite specimens from bedrock in Minnesota, which are nearly 2 billion years old. These specimens were sliced thinly, coated with oil to enhance visible details, and imaged with a high resolution flatbed scanner at Drury. The images were then emplaced in accurate three-dimensional computer reconstructions Ojakangas creates on his computer (Figure 21). Dr. Ojakangas has created complex computer models with which he attempts to recreate unique structures he has identified in these specimens. His models allow him to grow model stromatolites at an arbitrarily chosen latitude on an ancient earth with arbitrary obliquity. Figure 23 links to a simulation of stromatolite growth

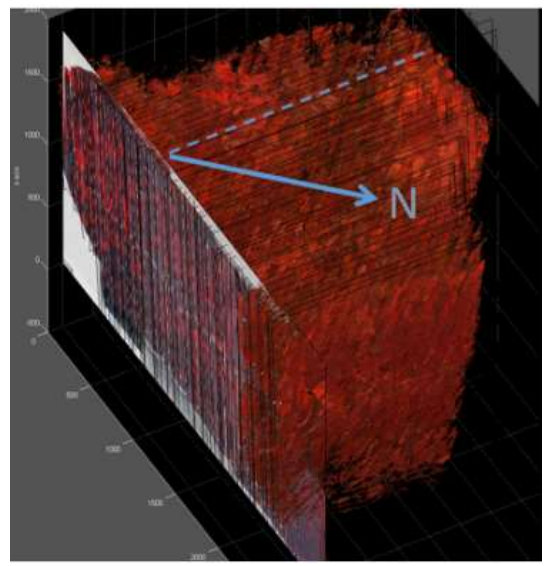

Figure 21: Three-dimensional computer representation of slabbed and scanned stromatolite specimen from the Mary Ellen Mine, Minnesota.

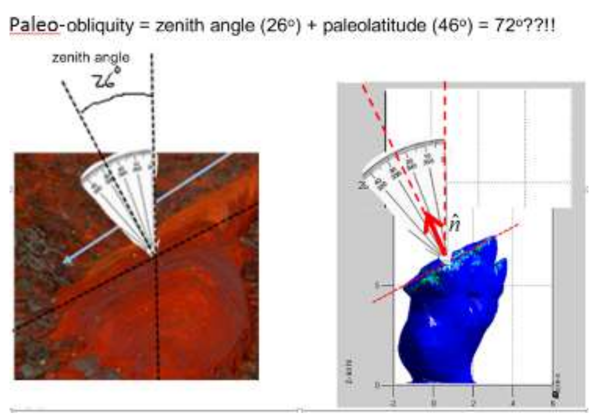

Figure 22: Model stromatolite (right) compared to actual slabbed specimen (left). Model suggests possible large earth obliquity 1.85 billion years ago.

over a period of 3 years for one particular set of parameters. Time of year is represented on the circular inset, with winter at the bottom and summer at the top of the circle. Among other results, his recent models suggest that 2 billion years ago, North America was rotated by 135 degrees relative to present orientation, and that the earth's obliquity may have been greater than 60 degrees! Within the past year (2014-2015) Ojakangas gave seminars on this work at Colorado State University, Missouri S&T, and the Geological Society of America Conference. He intends to submit this work for journal publication soon.

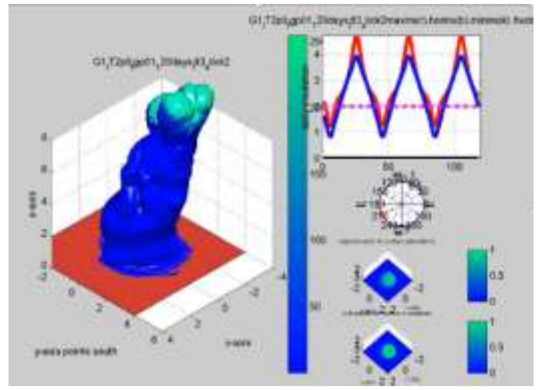

Figure 4: A simulation of stromatolite growth over several years using Ojakangas' computer model. Red dot on circle measures the seasons, with winter at the bottom.

Other research topics:

Dr. Ojakangas has many ongoing and previous research projects that are not described here, in order to keep this document of manageable length. If the reader has read this far, Dr. Ojakangas would be impressed!

Astronaut finalist

In 1994, while working as a professor at the University of Minnesota Duluth, Dr. Ojakangas was a finalist in NASA's astronaut selection program. Although traveling into outer space has always been one of his biggest dreams, he notes that two of his friends he met in the program, Rick Husband and Willie McCool (Commander and Pilot of the space shuttle Columbia), both perished in the Columbia disaster in 2003. Dr. Ojakangas is glad to be alive, and enjoys living on the earth very much.