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**Low Luminosity Compact Stellar Objects and the
Size of the Universe**

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Low Luminosity Compact Stellar Objects and the Size of the Universe

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Abstract

We have carried out an experimental and theoretical program in high-energy astrophysics. We participated in the creation of the Milagro Gamma Ray Observatory. This facility is a revolutionary advance in high-energy astrophysics that will be capable of observing TeV radiation from sources over much of the sky. We built a new class of compact, vibration-free solid state cryocoolers that will enable space-based infrared imaging and gamma-ray spectroscopy missions. We developed theoretical models that describe the dynamical processes in neutron stars and explain how variations in pulsar periods indicate the occurrence of starquakes. We computed the encounters between red-giant stars and other stars to determine whether these events could explain the observed depletion of red-giants towards the center of the galaxy. We studied chaotic stellar orbits in galactic potentials with the aim of understanding the equilibrium structures of galaxies and interpreting recent data from the Hubble Space Telescope.

Background and Research Objectives:

We developed the Milagro Observatory to allow the first systematic all-sky survey to be made at gamma ray energies. In addition, Milagro can provide study of time variability of sources that have previously been only observed on a limited basis. The scientific goal of this research is the study of astrophysical sources by the detection of very high-energy gamma radiation (above ~500 GeV). We will extend and expand the studies at lower energies, up to 10 GeV, which have revealed a number of point sources such as active galactic nuclei and supernova remnants, as well as diffuse emission, and emission from some gamma ray bursts.

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Neutron stars contain the densest matter outside of black holes. By analyzing their spin behavior, we aimed to learn about the properties of this matter and its dynamics. Isolated pulsars, which are magnetized neutron stars, do not spin down in a regular fashion. They suffer sudden jumps, glitches, in their spin rates which are believed to be due to the interaction of the neutron superfluid in their interiors with their solid crusts. We developed theoretical models to understand these interactions.

We worked to develop critical components for a cryocooler based on optical refrigeration that will allow the use of high-performance cryogenic detectors in astrophysical observations and remote sensing applications. When these cryocoolers are fully developed, they will be superior in several ways to currently available cryocoolers. Since they contain no moving parts, they are thus vibration free, rugged and ideal for space-based applications such as IR and high-energy resolution gamma-ray observations for astronomy and for remote earth sensing.

Stellar interactions and collisions are important in dense stellar systems such as the cores of normal galaxies (such as our own), globular clusters and the centers of Active Galactic Nuclei. Collisions between stars may substantially affect the population. We focused predominantly on the center of our own galaxy, exploring both the stellar contents and the variety of stellar collisions that occur within the central few parsecs. In particular we investigated collisions involving giant stars as an explanation for the observed paucity of highly luminous red-giant stars within the central 0.2pc.

Recent years have seen growing observational evidence, derived both from ground-based instruments and from the Hubble Space Telescope, that many galaxies may be more irregularly shaped than the nearly axisymmetric objects assumed as late as the 1970's. For example, the existence of twisted isophotes is interpreted as evidence for deviations from axisymmetry, and there is evidence that many systems do not even exhibit the symmetries of a triaxial ellipsoid. High resolution photometry of nearby objects has also shown that many galaxies may have central brightness distributions which, assuming mass traces light, correspond to "cuspy" centers. Concurrently, theoretical and numerical studies indicate that even regularly shaped galactic potentials should contain significant measures of chaotic orbits. To resolve these issues we have undertaken a study to determine, using analytic and/or numerical techniques, exactly what kinds of stellar dynamical equilibria can actually exist in galaxies.

Importance to LANL's Science and Technology Base and National R&D Needs:

This research uses techniques and technologies that closely relate to several of LANL's responsibilities. In particular, the computational efforts and the detector development work strengthen LANL's stockpile stewardship and nonproliferation programs. The work on the vibration-free cryocooler will be useful for non-proliferation detectors, as well as for space-borne astrophysical detectors. The computational tools developed in our studies of stellar orbits support the needs of the stockpile stewardship programs.

Scientific Approach and Accomplishments:

Present studies around 1 TeV have used air Cherenkov telescopes (ACT), optical instruments that detect the Cherenkov radiation produced in the atmosphere by the shower particles. This technique has been developed over many years and now has achieved high sensitivity. However, ACTs can only observe a given, small region of the sky, and only on clear moonless nights. Thus they cannot perform a TeV all-sky survey or a systematic search for sources of transient emission. We have developed Milagro to be the first detector capable of observing the entire overhead sky all of the time in the 1 TeV region. Milagro consists of a large, covered pond of water with photomultiplier tubes deployed to detect the Cherenkov radiation produced when shower particles traverse the water. Milagro is currently under construction at the Fenton Hill site in the Jemez Mountains near Los Alamos.

As an initial step we developed the Milagrito prototype detector to test the concept and the design prior to final construction. The experience with Milagrito has led to some important improvements in the Milagro design: for example, it demonstrated the importance of surrounding each photomultiplier tube (PMTs) with baffles to block light scattered from below. These improvements are now being incorporated into Milagro. However, Milagrito was a detector in its own right (although not as sensitive as Milagro) and gives the first glimpse of the TeV sky.

In the one and a half years that Milagrito collected data, it recorded over 9 billion events. This past year we honed the algorithms used to reconstruct the data; we also improved the calibration of the detector, which led to a better understanding of both the physical locations of the PMTs and the response of these tubes and of the electronics to Cherenkov photons.

After Milagrito was turned off, we reconstructed all of the data; a monumental task that included reading in over 24 terabytes of data.

The first object analyzed was the moon. The moon is not a source of gamma rays but rather should appear as a deficit in the distribution of events from the isotropic flux of cosmic rays. A clear deficit of events is seen near the true position of the moon: the apparent shadow of the moon is expected to be displaced due to the bending of the charged cosmic rays in the earth's magnetic field. Further analysis is needed to correct the data for this effect. Preliminary analysis also indicates that emission from Markarian 501, an active galaxy, has been detected with Milagrito.

We have developed a theoretical explanation for the irregular spin behavior of most isolated pulsars. Many of these objects suffer sudden jumps, glitches, in their spin rates. Persistent increases (offsets) in spin-down rate following glitches have been observed in the Crab pulsar, PSR 0355+54 and PSR 1830-08. In the Crab pulsar, these permanent offsets typically involve fractional changes in the spin down rate of $\sim 10^{-6}$ - 10^{-4} . These persistent increases are suggestive of permanent increases in the external torque acting on the star. Crust motions could change the orientation of the magnetic moment with respect to the spin axis and hence change the external torque. We were able show that these changes are evidence of starquakes, or faulting in the crusts of neutron stars. We modeled the star as a two-component homogeneous spheroid: a brittle crust of uniform density afloat on an incompressible liquid core. In equilibrium, the star has a spheroidal shape with an equatorial bulge. As the neutron star spins down, the fluid interior becomes more spherical, while strain develops in the rigid crust. The crust breaks once the strain reaches the elastic limit for the crustal material. The distribution of strain determines the geometry of the starquake. Our calculations found that the strain is largest at the equator, where a fault will begin forming once the crust breaks. There, an element of matter receives compressive stress until it yields. The break begins somewhere on the equator, along fault f or f' of Fig. 1.

The matter motions induced by the spin down distort the stellar magnetic field that is anchored in the crust, generating magnetic stresses that affect the development of strain. The magnetic field inhibits strain close to the magnetic poles, making starquakes most likely to originate at the two points on the equator farthest from the magnetic poles. From there, matter will move to higher latitudes allowing the equatorial circumference of the star to decrease.

The magnetic field, however, inhibits motion across field lines favoring breaks along fault f. As material moves along this fault, matter accumulates at higher latitudes, breaking the axial symmetry of the star's mass distribution.

These mass motions shift the principal axis of inertia of the star away from the angular momentum vector causing the star to precess. The damping of the precession will restore alignment of the principal axis of inertia and the angular momentum vector, increasing the angle between the rotation and magnetic. An increase in this angle is likely to strengthen the magnetic braking torque on the star and produces a permanent increase in the spin-down rate. We found that the release of the spin-down strain that develops between glitches in the Crab is adequate to produce observed offsets seen in the Crab pulsar. Furthermore, the reorientation of the magnetic axis translates into a reorientation of the radio emission beam with respect to the observer. This may produce a change in the pulse profile and the flux of order 1%, which may be measurable both in x-ray and optical bands

We have developed a proof-of-principle optical refrigerator that achieved 54 °C of cooling from room temperature with a heat lift of more than 25 mW. These measurements show that this optical cooler functions essentially as predicted by theoretical models, validating the physics necessary to develop practical, cryogenic optical refrigerators.

The basic principles for optical refrigeration have been discussed for many decades: When nearly monochromatic radiation passes through certain condensed materials, the light is absorbed and reradiated at a higher frequency. Since the increase in the energy of the photons is supplied by thermal phonons in the material, the object cools. Though simple in principle, actually cooling by this process has proven difficult, since a myriad of processes can turn light into heat and mask the optical refrigeration effect. Only recently has optical refrigeration using a ytterbium-doped fluoride glass been demonstrated in the laboratory by us and our colleagues.

To test the basic principles of optical refrigeration we constructed a device that embodied most of the features of an optical refrigerator. The cooling element is a cylinder of ytterbium-doped fluoride glass that mirrored on both ends; one mirror has a 150-micron diameter pinhole for admitting the pump radiation.

Low-thermal-conductivity, optical fibers support the cooling element inside a copper whose interior walls of this cooler chamber are coated to absorb the fluorescence while having a low emissivity at thermal wavelengths (3-20 microns). The entire cooler is placed in a large vacuum vessel to decrease the thermal conduction between the glass and cooler chamber.

The ytterbium-doped glass cools when the appropriate wavelength light from a laser is focused through the hole in the mirror. The cavity created by the mirrors on the ends of the cylinder traps the pump radiation until it is absorbed by the ytterbium. The ytterbium ions fluoresce at a shorter mean wavelength than the pump radiation. The energy difference between the fluorescent and pump photons is supplied by the absorption of thermal phonons; the removal of these phonons cools the glass. The fluorescence is absorbed by the cooler chamber walls which carry away the energy from the pump laser. A temperature-control system keeps the cooler chamber at a constant temperature. Thermocouples glued to the glass, cooling element and to the copper chamber measure their temperatures.

Figure 2 shows one cool-down experiment when the laser pumped the optical cooler with 1.6 watts of light at a wavelength of 1030 nm. The temperature of the cooling element decreased to -32°C compared to the chamber temperature of 22°C ; i.e., a temperature drop of 54°C . The glass temperature follows a nearly exponential cooling curve with a time constant of ~ 65 minutes.

The performance of the current device is primarily limited by the ~ 2 watt laser source used in these experiments. A practical cryocooler would be driven by efficient, high-power diode lasers ($\sim 100\text{W}$). With the use of more powerful lasers and improvements in the mirroring and processing of the cooler elements, an efficient, compact, all solid-state cryocooler should be possible. The work under this project has found no apparent barriers to the implementation of a practical, optical refrigerator operating at cryogenic temperatures.

The densities of galactic-center clusters are sufficiently large for stellar collisions to be important. Though many galaxies will have central populations similar to that of our own, their distances preclude comparable spatial resolution. The galactic center population may not be resolved as easily as other dense systems, such as globular clusters, but its population differs substantially from such clusters. Whereas the populations of globular clusters are very old, the galactic center population almost certainly contains a young stellar population (as well as an older one) and may have had an ongoing star formation history.

In the galactic center, therefore, the masses and evolutionary stages of colliding stars may well differ from those in globular clusters. The outcomes of collisions will also depend on whether the collisions occur in the galactic center or in globular clusters. The core velocity dispersions of globular clusters are about 10 km/s, much less than the surface escape speeds of the colliding stars. Close collisions between stars in globular clusters thus lead to bound systems. In comparison, the galactic center likely contains a supermassive black hole often that increases the local velocity dispersion to a few-hundred km/s. This value is comparable to the surface escape speeds of stars and so the outcome of stellar collisions will depend on the species of stars being considered.

We have explored both the stellar contents and the variety of stellar collisions that occur within the central few parsecs. In particular we have investigated collisions involving giant stars as an explanation for the observed paucity of highly luminous red-giant stars within the central 0.2pc. Such stars are likely to have been asymptotic giant-branch (AGB) stars of intermediate mass (approximately $2-4M_{\text{solar}}$), although their masses could have been higher (e.g. about $8 M_{\text{solar}}$).

We investigated into collision rates in the galactic center and simulated the outcomes of a wide range of collisions between giant stars with a variety of single or binary impactors. The amounts of mass lost from the giant in such collisions have been evaluated and the frequencies of collisions that lead to the destruction of the giant have also been obtained. Under the assumption that the giant stars were on circular orbits, their data indicate that collisions which may destroy the giant do occur, but do not take place sufficiently frequently to account for the absence of all the brightest giant stars within the central 0.2pc of our galaxy.

An explanation of the bright giants' paucity remains outstanding. There exist a number of collision mechanisms that have not yet been investigated. These include two-body and binary-single collisions involving stars prior to evolving into the luminous giants. We have also considered the fate of luminous giants that have eccentric orbits that take them extremely deep into the unresolved nucleus of the galaxy. In the eccentric orbit case, a very dense stellar population is required. Such a population could be an undetected sub-population of stellar black holes, but the dynamical constraints against such a population are strong.

We identified two routes via which giant stars might be destroyed as a result of a collision. Firstly, a sufficiently violent encounter might expel enough of the envelope to immediately destroy the giant. Secondly, the impactor may lose enough of its orbital energy to become bound to the giant star. Such a collision might not necessarily involve prolific instantaneous mass loss, but the bound system formed is likely to evolve into a common envelope system. In such systems the impactor and the giant's core orbit each other within the giant's envelope. Transfer of energy and angular momentum from the orbiting pair to the envelope may force the expulsion of the envelope; i.e. the initial collision leads ultimately to the destruction of the giant. We found that although some collisions do indeed destroy the giant, destructive collisions do not occur sufficiently frequently to account for the absence of all the giant stars.

Recently high resolution photometry of nearby objects has also shown that many galaxies may have central brightness distributions which, assuming mass traces light, correspond to "cuspy" centers that are much sharper than the smooth cores associated, e.g., with a King model. Concurrently, there has emerged theoretical and numerical evidence indicating that even if regularly shaped galactic potentials are often nearly integrable and dominated by regular orbits, irregularly shaped galaxies should contain significant measures of chaotic orbits. The amount of chaos is also increased significantly if the central region is perturbed in such a fashion as to mimic the effects of a supermassive black hole and/or cusp. Detailed analyses of N-body simulations have also shown that, in a number of different settings, notably near resonances in a rotating barred galaxy, chaos may be present and play an important role.

In light of the preceding, there is an obvious need to determine, using analytic and/or numerical techniques, exactly what kinds of equilibria can actually exist. We have concentrated on three main areas: analytic and numerical analysis of the collisionless (collisional) Vlasov (Landau) equation, the effect of noise on phase space transport, and error and convergence analysis of stochastic partial differential equations. Our analysis of transport equations has focused on questions such as the utility of moment expansions, the meaning of chaos at the level of the distribution function, and the development of numerical schemes for the solution of the Vlasov-Poisson and Landau equations. The question of the relevance of chaos to transport theory involves understanding the connection between the statistics of the individual particle orbits and the full distribution. One of the eventual aims of our work is to identify the dynamical mechanisms underlying the theory of violent relaxation.

We have identified the importance of first-passage time statistics in probing the rate at which individual orbits diffuse through cantori to move from being confined to unconfined. Another related topic under investigation is the approach towards an invariant distribution exhibited by initially localized ensembles of chaotic orbits evolved in 3-D potentials. The new feature is that there can be two unequal positive Lyapunov exponents.

Contrary to conventional wisdom, we have shown that one can (at least in principle) build equilibria that do not depend only on isolating integrals. However, these equilibria require finely tuned phase space structures, so (i) to the extent this is like constructing an equilibrium that depends on isolating integrals in a complicated way, might expect these to be less stable than simple spherical and axisymmetric equilibria, and (ii) such structures are probably harder to make or sample, so one might expect that real triaxial galaxies are "less close to" real equilibria. Additionally, we have considered two sorts of perturbations, namely: low amplitude friction and noise, which can serve as a source of extrinsic diffusion; and low amplitude periodic driving/modulation, which can serve as a source of modulational diffusion. If white, or nearly white, noise can model discreteness effects within a galaxy and that colored noise and/or periodic driving can model effects of companion/satellite galaxies and/or other neighboring objects, then the basic questions are: (i) when are these effects important on astronomically relevant time scales? (ii) to what extent does the detailed form of the perturbation matter? (iii) what is the physics that is inducing the effects? Conclusions reached to date are: (i) Small scale effects can be important on a Hubble time, (ii) For "reasonable" choices of multiplicative noise, the details seem largely irrelevant. Moreover, the presence or absence of friction also has at most minimal effect. This was tested by performing first passage time experiments, determining as a function of amplitude how fast noisy orbits can leak through cantori. (iii) The presence of colored noise (e.g., noise characterized by a finite auto-correlation time) is unimportant provided only that it is short compared with a characteristic dynamical. The astronomical implication of this work is that if the details of the friction/noise are largely irrelevant, a substantial simplification results: what one would expect to see should not depend sensitively on inputs that are not easily accessible observationally. All that would really matter is the amplitude, which is usually easy to estimate via dimensional analysis.

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Figures:

Figure 1: Fault propagation in the presence of a strong magnetic field occurs preferentially along fault f , creating mound (indicated by the snow-capped peaks) and shifting the largest principal axis of inertia to a new direction.

Figure 2: Temperature measurements as the optical cooler is pumped by 1.55 watt of 1030 nm laser light. The upper curve is the temperature of the outer wall of the cooler chamber. The lower curve is the temperature of the cylindrical glass cooling element.

Optical Refrigerator Performance