

**Final Technical Report for NASA Grant NCC554**  
**Cooperative Research in High Energy Astrophysics**

**August 15, 1993 ----- July 31, 1997**

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**This grant covered the period August 15, 1993 through July 31, 1997. The research covered a variety of topics including:**

- 1. Detection of cosmic rays and studies of the solar modulation of galactic comic rays**
- 2. Support work for several X-Ray statellites**
- 3. High resolution gamma-ray spectroscopy**
- 4. Theoretical Astrophysics**
- 5. Study of Active Galaxies**

**Details of the research are appended.**

## 1.2 Summary of Current Programs

### 1.2.b Research Groups at Goddard Space Flight Center (Laboratory for High Energy Astrophysics)

1. **Low Energy Cosmic Ray Group** Study the energy spectra and the abundances of elements and isotopes in the solar system or from the galaxy. These particles of 1 - 1000 MeV energies are accelerated by a variety of physical mechanisms at the sun, in planetary magnetospheres, and in interplanetary and interstellar space. Measurements are made using solid-state telescopes on spacecraft traveling throughout the heliosphere.
2. **High Energy Cosmic Ray Group** Cosmic rays provide a unique probe of the most energetic processes in the Universe. While astronomical observations of electromagnetic radiation from distant objects yield clues to the processes and the state of matter in our galaxy and beyond, cosmic rays bring us a small but valuable sample of that matter itself. Through studies of the composition and energy spectra of cosmic rays, it is possible to learn about the origin and evolution of material in our galaxy and about fundamental processes that govern its dynamics. This work involves both balloon-borne and space-based experiments.
3. **X-ray Astrophysics Group** The X-ray group has an active program developing detector technologies, developing instruments for flight, interpreting observations, and constructing models of astrophysical systems and processes. X-rays provide some of the best probes for studying neutron stars, black holes, the missing mass in galaxies and clusters, and the hot plasma of supernovae and we have personnel working in all these subfields.
4. **Low Energy Gamma Ray Group** This research group specializes in high-resolution spectroscopy and in studies of steady and transient behaviors of astrophysical sources of gamma radiation. Of particular interest are the time-varying galactic center source of annihilation radiation, other celestial sources that exhibit nuclear gamma ray line emission, and the cosmic gamma-ray bursts. These phenomena are windows to some of the basic high energy astrophysical processes in Nature. They have recently completed balloon-borne observations of the supernova SN87a and are looking forward to several next-generation spacecraft instruments in gamma ray spectroscopy that will present a variety of laboratory opportunities.
5. **High Energy Gamma-Ray Group** Because gamma-rays are the most energetic photons, the study of cosmic gamma-rays provides information about the largest energy transfers in the universe. For example, sources of high energy gamma-rays includes pulsars and quasars; analysis of gamma-ray data provides insight into the structure and dynamics of our Galaxy. The High-Energy Gamma-Ray Group at Goddard Space Flight Center is

involved in all phases of experimental gamma-ray astrophysics-- from the design, testing, and operation of detectors to the analysis and interpretation of data.

**6. Theoretical High Energy Astrophysics** Theoretical research in the LHEA is pursued in x-ray, x-ray and cosmic ray astrophysics as well as in extragalactic astronomy, cosmology, the physics of compact objects and solar physics. Theoretical studies are essential in order to determine the most important directions to pursue in future measurements, the interpretation of existing observations within a self-consistent framework, and in development of new experimental techniques.

## **2. Summary of Current Work**

A joint agreement between NASA/Goddard and The University of Maryland currently supports cooperative research in Satellite Based Studies of Photons and Charged Particles in the following areas:

- 1) Detection of cosmic rays and studies of the solar modulation of galactic cosmic rays
- 2) Research with several past and upcoming X-ray satellites
- 3) High resolution gamma-ray spectroscopy of celestial sources
- 4) Theoretical astrophysics

This section describes the current work in the various research areas covered by the current cooperative agreement and the proposed joint effort under CHEAR.

### **2.1 Cosmic Rays**

Cosmic rays are the only samples of matter which reach earth from outside the solar system. as such, they carry information on their origin, acceleration, and subsequent propagation.

#### **2.1.1 Cosmic Ray Detection**

Between the present low energy antiproton measurements, which extend up to about 1 GeV and the higher energy measurements except those of Bogomolov, which have error bars extending over an order of magnitude. In the summer of 1992, we flew the Isotope Matter Antimatter Experiment (IMAX) which took data on antiproton fluxes from 100 MeV to about 3 GeV. The experiment utilized the NASA Balloon Borne Magnet Facility (BBMF). Analysis of this data is ongoing.

Another experiment in which this group is involved is the MASS (Matter-Antimatter Spectrometer) experiment, which had a flight in the fall of 1992. This experiment has taken data on antiprotons in the 5-10 GeV range, as well as making positron measurements up to about 20 GeV.

### 2.1.2 Low Energy Cosmic Rays

Ian Richardson has continued the analysis of the extensive energetic particle data from the Goddard Space Flight Center instruments on the IMP 8, ISEE 3/ICE and Helios 1 and 2 spacecraft. A major focus of this work has been to use energetic particles as a diagnostic of the presence and structure of ejecta, the interplanetary manifestations of coronal mass ejections at the Sun. These studies have been made in collaboration with Dr. H.V. Cane (University of Tasmania, Australia), Dr. C.J. Farrugia (University of New Hampshire), Dr. T.T. von Rosenvinge (GSFC), and Prof. G. Wibberenz (University of Kiel, Germany). Ejecta are responsible for major geomagnetic storms and for the generation of transient interplanetary shocks, but studies of their propagation through the solar wind are hampered by the absence of a unique signature in the solar wind. Using the counting rates of the anti-coincidence guards of instruments on IMP 8 and Helios 1 and 2, the interaction of ejecta and cosmic rays has been studied. We find that ejecta produce characteristic short-term decreases in the intensity of particles from 10s of keV to cosmic ray energies which provide a reliable signature of the presence of an ejecta in the solar wind. Using the particle data, we have characterized the solar wind structures causing the major cosmic ray depressions during the 30 year period 1964-1994. Of the 153 events, 86% were caused by mass ejections and the related shocks. The largest depressions were observed when the ejection originated within 50° of the Sun's central meridian and the ejecta intercepted the spacecraft. Our studies clearly demonstrate that the ejecta, by excluding a fraction of cosmic rays from the interior, is a major factor in producing cosmic ray "Forbush" depressions even though this effect is ignored in current models of such events. The large-scale magnetic structure of ejecta is difficult to infer using spacecraft observations. They may be disconnected, closed structures (plasmoids) or include looped field lines rooted at the Sun at each end. From studying the flows of solar energetic particles in ejecta following solar events, we find evidence that field lines are connected to the Sun (since particles arrive rapidly after the event), and are probably looped since particles may first arrive from the east or from the west of the Sun and then develop bidirectional flows. Such flows are virtually absent in the solar wind outside ejecta. It has recently been suggested that looped ejecta field lines may reconnect with those in the ambient solar wind. In this case, we might expect to see characteristic particle enhancements inside ejecta. Since we do not appear to see such enhancements, we conclude that ejecta are predominantly closed structures. Energetic particles also provide a method of relating an ejecta with the related phenomena (e.g. flare, disappearing filament) on the Sun by considering the particle onset time and the intensity-time profile which shows characteristic features for events east and west of the observer, or

near the central meridian. This is important since potentially, knowledge of the location of the event can allow the magnetic field structure of the ejecta to be inferred and hence its potential for causing geomagnetic activity to be forecast. Unfortunately, most studies attempting to relate geomagnetic activity with ejecta and solar events have not considered energetic particle data and some clearly erroneous associations have resulted.

We have also shown that regions of abnormally low proton temperature in the solar wind provide a useful indication of ejecta, in addition to energetic particle depression. Using nearly 30 years of data, we demonstrated that the occurrence rate of low temperature plasma follows the solar activity cycle and in particular, the rate of coronal mass ejections observed by coronagraphs during the later part of the period studied. Another generally accepted signature of ejecta is abnormally low plasma electron temperatures, but we have shown that this is not correct. There is no consistent behavior of the electron temperature in ejecta. In particular, it is clearly enhanced rather than depressed in some ejecta.

The anti-coincidence guard data, which have a time resolution of 30 minutes, have also allowed us to investigate the modulation of the cosmic ray density by corotating high-speed streams in much more detail than previous studies which used daily-averaged neutron monitor data. The observations are consistent with modulation by the increased solar wind speed. Similar modulations were observed at high heliographic latitudes by the Ulysses spacecraft and, by comparing the modulations in the ecliptic and at Ulysses, we hope to learn more about the structure of high-speed streams and how they interact with cosmic rays. At lower energies, a preliminary study of corotating MeV ion enhancements associated with corotating streams at Earth and at Ulysses suggests that such events become more intense in the outer heliosphere in the ecliptic, consistent with acceleration at corotating shocks formed in the outer heliosphere. The intensity then falls off as the heliographic latitude increases and the corotating shocks become weaker.

A minor study of the Earth's magnetosphere has been made using the ISEE 3/ICE  $> 0.2$  MeV electron data obtained during the geotail phase of the ISEE 3 mission, in conjunction with J.A. Slavin (GSFC) and C.J. Owen (Queen Mary and Westfield College, London). The data provide insight into the structure of the geomagnetic tail, such as the presence of open or closed magnetic field lines, and its evolution during geomagnetic substorms.

## 2.2 X-ray Astronomy

Scientists associated with the University of Maryland that have conducted research in X-ray astronomy at NASA/Goddard Space Flight Center in the last year comprise Dr. Keith Arnaud, as an Associate Research Scientist, Dr. Keith Gendreau, as a Research Associate, Dr. Mike Stark, as a Research Associate, and Dr. Scott Porter, as a Research Associate. Five new Research Associates have recently joined this program: Dr. Una Hwang, Dr. Michael

Lowenstein, Dr. Greg Madejski, Dr. Fred Finkbeiner, and Dr. Caleb Scharf. In addition, four University of Maryland graduate students are working on their thesis projects with the Goddard X-ray astronomy group. These are Damian Audley, Warren Focke, Don Horner, and K.D. Kuntz. Jeonghee Rho successfully defended her thesis during the past year and departed to take up a postdoctoral position at Saclay. As usual, a number of other University of Maryland students worked with the X-ray group over the summer.

Keith Arnaud has continued his work with ASCA (Advanced Satellite for Cosmology and Astrophysics). As part of the Guest Observer Facility he is responsible for software development and maintenance, for assisting in planning observations, for answering guest observer's questions, and for ensuring that information flows from the hardware teams to the outside world. The XSPEC spectral fitting program that he maintains and improves continues to gain acceptance as the world standard in this field. On the science side Arnaud has worked on X-ray observations of clusters of galaxies, radio galaxies, and a planetary nebula.

Keith Gendreau worked on several calibration issues for ASCA. Specifically, he addressed problems with the optical constants used for the X-ray Telescope (XRT) simulations. He has also participated in reviews for AXAF and XMM calibration. For XMM, he was asked to present a comprehensive review of the ASCA calibration. He has also started working on the ASTRO-E X-ray microcalorimeter. For this project, he has been studying X-ray properties of the absorbers of the calorimeters. In addition, he has been reconstructing a double crystal monochromator for use in the ASTRO-E calibration. Some of this work was done with a summer graduate student, Gary Pennington, from the University of Maryland. Keith has also continued work on the analysis of the spectrum of the Cosmic X-ray Background (XRB) with ASCA and ROSAT data. A paper on the results has been accepted for publication in the MNRAS.

Michael Stark continued work with the Proportional Counter Array group of the Rossi X-ray Timing Explorer (RXTE). He has been primarily responsible for developing a model of the background in the proportional counters to be used with RXTE data in spectral studies of faint x-ray sources. The launch of RXTE was contemporaneous with the discovery of the bursting pulsar (GROJ1744-28) and Michael Stark has studied this new source in the data which was generated by the frequent monitoring of the source by RXTE. He also is the principal investigator for an observation of Cygnus X-3 which was made this year.

Scott Porter spent the last year working on the X-ray Quantum Calorimeter sounding rocket experiment. During that time the rocket was launched twice from White Sands Missile Range in New Mexico. The experiment consists of a 36 pixel microcalorimeter array with a nominal spectral resolution of 10eV in the band from ~30eV to 3.3keV with a 28 degree field of view. The goal of the experiment is to look at the soft X-ray background in the band

from 30eV to 1keV. A mechanical failure during the first flight precluded the acquisition of any meaningful data. In the second flight, however, the experiment worked well and several hundred seconds of data were collected. Porter has worked extensively on both the flight hardware and the post-flight data analysis. Porter's other main activity was the continued development of other advanced x-ray detectors. A new superconducting transition edge sensor program was started as well as further optimization of the microcalorimeter detectors.

Damian Audley has been investigating the high mass binary X-ray pulsar Centaurus X-3 using observations from ASCA and EXOSAT. His work on advanced X-ray detectors included investigating YBCO as a possible absorber material.

Warren Focke, with Dr. Jean Swank, has been investigating the low-mass X-ray binary Cygnus X-2 through analysis of X-ray light curves and spectra collected by the Rossi X-ray Timing Explorer (RXTE). The system is believed to consist of an accreting neutron star in a binary orbit with a small evolved companion star. He has recently published (The Astrophysical Journal, 470:L127-L130, 1996 October 20) the first measurements of the spin frequency (165 Hz) and magnetic field ( $2.2 \times 10^9$  G) of the neutron star. Focke is also, with Dr. Swank and Dr. Lev Titarchuk, continuing his investigations of the black hole candidate Cygnus X-1 through analysis of data from RXTE and the Japanese GINGA satellite. This source recently entered its rare, and until now poorly studied, high, or soft, state. This state shows timing properties quite different from those seen in the more common low/soft state, including the absence of the quasiperiodic oscillations usually seen.

Don Horner has worked on the WARPS (Wide Angle ROSAT Pointed Survey), a search for galaxy clusters serendipitously observed in ROSAT PSPC data. His main responsibilities have been analyzing the optical imaging data on the cluster candidates.

### **2.3 Low Energy Gamma-Ray Astronomy**

The main focus of this research is high resolution gamma-ray spectroscopy of celestial sources in the 20 keV to 10 MeV energy range. The principle experimental objective of this program is to search for and study narrow lines in the low-energy gamma-ray spectrum. Such lines can be produced by 1) cosmic ray induced emission from nuclear excited states, 2) remnant radioactivity from nucleosynthesis, 3) positron annihilation, and 4) cyclotron line emission from the strong magnetic field regions near the poles of a neutron star. Observational evidence exists at present for processes 2), 3), and 4). The technique of nuclear spectroscopy applied to astrophysics promises to be a powerful new diagnostic tool for probing high-energy astrophysical processes such as are known to exist in the vicinity of neutron stars and black holes. This is a young field, but already results are in hand that conclusively demonstrate the potency of the method. The principle experimental activity

within this program is the development and operation of balloon- and satellite-borne instrumentation that perform high-resolution gamma-ray spectroscopy using Germanium detectors. In addition, ground based optical instrumentation is being developed to support the balloon and satellite observations. The individual programs are described briefly as follows:

### 2.3.1 Gamma-Ray Imaging Spectrometer (GRIS)

GRIS is a very sophisticated and powerful gamma-ray telescope that is carried above the earth's atmosphere on high altitude balloons. The basic experiment consists of an array of seven large high-purity Germanium detectors to make precise measurements  $E/\Delta E \sim 500$  of gamma-ray energies in the 20 keV to 10 MeV range. The detector array is surrounded by a thick massive anti-coincidence shield to suppress the strong atmospheric and instrumental gamma-ray background flux. In addition there is an active NaI coded-aperture mask that will produce gamma-ray images over a  $9^\circ \times 15^\circ$  field of view. GRIS measures gamma-ray fluxes that are five to ten times weaker than could be detected by the best previous instruments. GRIS was first flown successfully in 1988 from Alice springs, Australia. Exciting new results were obtained on the Galactic Center arc SN 1987. It will be flown 1-2 times yearly over the next 5 - 6 years.

### 2.3.2 Transient Gamma-Ray Spectrometer (TGRS)

The TGRS is an already existing satellite-borne gamma-ray spectrometer intended to perform high resolution studies of the spectra of gamma-ray bursts. It is flying on the WIND spacecraft that is part of the Global Geospace System (GGS), a new multiple-spacecraft mission to be launched. Its primary purpose is to make the first precise detailed studies of the lines that are known to exist in the spectra of gamma-ray bursts. Two kinds of lines have been observed. First, lines in the vicinity of 50 keV occur in many bursts. They are believed to result from electron cyclotron emission in the enormous magnetic fields ( $10^{12}$ ) gauss that are typically present at the poles of neutron stars. Second, lines in the vicinity of 400 keV have been observed in 10% of the bursts. These are believed to be due to electron-positron annihilation (511 keV) radiation produced near the surface of a neutron star. This radiation is subsequently redshifted as it escapes the strong neutron star gravitational field. If this is true then it represents the first direct measurement of the gravitational potential of a neutron star. The basic instrument consists of a single Germanium crystal radiatively cooled to a temperature of 95K. The detector is unshielded and nearly omnidirectional as the gamma-ray burst may come from any random direction in the sky. It will make spectral measurements with typically 40 times better energy resolution than the best previous instrument.



### 2.3.3 Rapidly Moving Telescope (RMT)

RMT is a ground based optical telescope capable of slewing to any target on the sky in less than one second, tracking the target with sub-arcsecond stability, and imaging it with one arcsecond resolution. It can see objects as faint as 15-th magnitude with one second exposures. Its purpose is to locate and identify the optical counterpart flash to Gamma Ray Burst events. It will operate in conjunction with the MIT Explosive Transient Camera. The RMT instrument is able to move so quickly, because unlike a traditional telescope, only the mirror assembly moves (an azimuth-elevation mechanism); thereby picking out a patch of the night sky and reflecting it into a fixed telescope. Imaging is done with a CCD camera. The instrument is designed to operate totally automated. The observing program and data analysis is all computer controlled. Currently the instrument is undergoing integration and shakedown operation at Kitt Peak. First sky observations occurred in 1991.

### 2.3.4 Gamma-Ray Astronomy

The EGRET instrument on the Compton Gamma Ray Observatory covers the energy range from about 20 MeV to 30 GeV and has made a number of significant discoveries in both galactic and extra-galactic gamma ray astronomy. These include the measurement of the high energy gamma ray emission properties from pulsars, quasars, and BL Lac objects. Observations of gamma ray burst have led to the discovery of surprising aspects of these mysterious events. A detailed study of the galactic diffuse radiation to study the galactic cosmic ray distribution and galactic dynamics is also in progress.

To continue these advances, the design of a next-generation gamma-ray telescope is under study. In collaboration with scientists at Stanford University and SLAC, we are studying both silicon strip and gosmicrostrip detectors for a gamma-ray telescope that will have ten times the sensitivity of EGRET.

Summer research opportunities and Ph.D. thesis possibilities exist for students interested in these areas.

## 2.4 Theoretical Astrophysics

Theoretical studies are essential in order to determine the most important directions to pursue in future measurements, the interpretation of existing observations within a self-consistent framework, and in the development of new experimental techniques. Theoretical research is pursued in X-, gamma- and cosmic ray astrophysics, as well in extragalactic astronomy, cosmology, compact object astrophysics, and solar physics.

The theory group has supported two graduate students doing thesis research at the Goddard

Space Flight Center.

Jason Taylor is continuing his graduate work with Dr. Demos Kazanas on modeling the optical and UV line emission from active galaxies under the assumption that these lines are due to reprocessing of the non-thermal radiation by red giant stars in the cluster near the active nucleus. Taylor has calculated the line profiles and the 1D and 2D line transfer functions for this system.

Ramin Sina is working with Dr. Alice Harding on a thesis project involving the investigation of processes in strong magnetic fields and their application to radiation from neutron stars. This past year, Sina completed his Ph.D. thesis on analytic and numerical calculation of the Trident production and electron-positron scattering cross sections.

## **2.5 Active Galaxies**

This work has been carried out by Sylvain Veilleux and collaborations.

### **2.5.1 Obscured Broad-Line Regions in Seyfert 2 Galaxies**

A search for obscured broad-line regions in Seyfert 2 galaxies was carried out. For this purpose, we acquired high-quality infrared (J, K, and L bands) spectra of 33 galaxies. It was found that a surprisingly large fraction (perhaps as much as 25%) of the objects in our sample present a hidden broad-line region. In the standard unification theory of Seyferts, this high frequency of partially obscured Seyfert 2s implies that the transition zone located between the optically-thin “throat” of the torus and the optically-thick core is rather extended. We are now comparing our data with the predictions of various models. A paper describing the preliminary results of this study was published in 1993 (ApJ, 422, 521). The final results of this study have now been accepted for publication in the *Astrophysical Journal* (Veilleux, Goodrich, & Hill 1996).

### **2.5.2 The Nature of Ultraluminous Infrared Galaxies**

The results of a large spectroscopic study of 200 luminous infrared galaxies have now been published (ApJS, 98, 129 and ApJS, 98, 171). Extrapolation of this type of study to a large unbiased sample of ultraluminous IRAS galaxies is now underway, the first results of which have been submitted recently to the *Astrophysical Journal*. We find that the fraction of Seyfert galaxies increases dramatically above  $\log [L_{\text{IR}}/L_{\odot}] = 12.3$ . Nearly half of the galaxies with above this limit present Seyfert characteristics. As expected, photoionization by hot stars appears to be the dominant source of ionization in the objects with H II region-like spectra. We present additional evidence that the ionization source in infrared-selected galaxies with nuclear LINER-like spectra (approx. 40% of the ULIGs in our sample) is likely

to be shocks or of stellar origins rather than an AGN. Shock ionization associated with starburst-driven outflows may also explain the LINER-like emission detected outside the nuclei of some galaxies.

### 2.5.3 The Effects of Nuclear Activity in Galaxies on the Surrounding Environment

The results of detailed Fabry-Perot studies of the Seyfert galaxy NGC 3516 and the infrared-luminous galaxy NGC 3079, host of a spectacular nuclear bubble-like outflow, have been published (AJ, 105, 1318; ApJ, 433, 48; ApJ, 445, 152; ApJ, 452, 613). Various models were considered to explain the bizarre Z-shaped emission line region in NGC 3516. In NGC 3079, we found that the starburst (rather than the AGN as originally thought) was probably the main driver of this outflow. We also found that the vertical disk structure of this galaxy is regulated by intense star formation throughout the disk. The results of Fabry-Perot studies on half a dozen similar objects are now either in press (e.g., Circinus Galaxy: Veilleux & Bland-Hawthorn 1995), or about to be submitted to the Astrophysical Journal. The scientific consequences of our results have recently been summarized in a Scientific American article (Veilleux, Cecil, & Bland-Hawthorn 1996).

### 2.5.4 The Gaseous Extent of Galaxies

A search for faint diffuse line emission in the outskirts of spiral galaxies is presently being carried out with S. Vogel (UMD), J. Bland-Hawthorn (AAO), R. Weymann (Carnegie), and C. Carignan (U.Montreal) using imaging Fabry-Perot interferometers on the Anglo-Australian, the William Herschel, the Las Campanas, and Canada-France-Hawaii Telescopes. Preliminary results suggest the presence of faint  $H_{\alpha}$  emission beyond the H I edge of some spiral galaxies. Once confirmed, it is hoped that these data will provide constraints on the distribution of the dark matter halo in these galaxies.

## 3. Future Efforts

Many of the projects described previously are ongoing and work will continue in the investigation of the relevant phenomena. Some more specific details are given below.

### 3.1.1 Cosmic Ray Detections

Some of the most significant questions in the field of particle astrophysics can be addressed by measurements of the isotopic composition of the cosmic radiation. The radioactive clock isotope  $^{10}\text{Be}$ , with a half-life of  $1.5 \times 10^6$  years, is a particularly important case. Measurements of the abundance of this isotopes to relativistic energies, where time dilation effects become appreciable, will probe the density distribution of interstellar matter in the volume in which cosmic rays propagate. The Isotope Magnet Experiment (ISOMAX) is

1995-1996

**6. Theoretical High Energy Astrophysics** Theoretical research in the LHEA is pursued in x-Ray, x-ray and cosmic ray astrophysics as well as in extragalactic astronomy, cosmology, the physics of compact objects and solar physics. Theoretical studies are essential in order to determine the most important directions to pursue in future measurements, the interpretation of existing observations within a self-consistent framework, and in development of new experimental techniques.

**2. Proposed Joint Effort of the University of Maryland and the NASA Goddard Space Flight Center Laboratory for High Energy Astrophysics.**

This grant supports activities conducted by University personnel both on campus and at the Goddard Space Flight Center. Work will be concentrated in the following areas:

- 1) Detection of cosmic rays and studies of the solar modulation of galactic cosmic rays
- 2) Research with several past and upcoming X-ray satellites
- 3) High resolution gamma-ray spectroscopy of celestial sources
- 4) Theoretical astrophysics

This section describes the work accomplished to date and the proposed joint effort for the next grant period for each of these areas within the overall research program. During the upcoming year, we propose to continue our joint efforts in the areas listed above.

**2.1 Cosmic Rays**

Cosmic rays are the only samples of matter which reach earth from outside the solar system. as such, they carry information on their origin, acceleration, and subsequent propagation.

**2.1.1. Cosmic Ray Detection**

Between the present low energy antiproton measurements, which extend up to about 1 GeV and the higher energy measurements except those of Bogomolov, which have error bars extending over an order of magnitude. In the summer of 1992, we flew the Isotope Matter Antimatter Experiment (IMAX) which took data on antiproton fluxes from 100 MeV to about 3 GeV. The experiment utilized the NASA Balloon Borne Magnet Facility (BBMF). Analysis of this data is ongoing.

Another experiment in which this group is involved is the MASS (Matter-Antimatter Spectrometer experiment, which had a flight in the fall of 1992. This experiment has taken data on antiprotons in the 5-10 GeV range, as well as making positron measurements up to about 20 GeV.

### 2.1.2 Low Energy Cosmic Rays

Ian Richardson has continued analysis of energetic particle data from IMP 8, ISEE 3/ICE and Helios 1 and 2. Further studies of cosmic ray depressions have been made with H.V. Cane (U. of Tasmania) and G. Wibberenz (U. of Kiel) using anti-coincidence guard data. Two papers on multi-spacecraft observations of such depressions have been published in J. Geophys. Res. Another paper submitted to JGR discusses the relationship between energetic particle and plasma proton temperature depressions, and other ejecta signatures. Cosmic ray depressions observed in 1964 to present have been examined using neutron monitor, solar wind and spacecraft energetic particle data to determine the relative roles of shocks, ejecta, and corotating streams in causing these decreases. Depressions observed at Earth caused by shocks remote from the Earth have been investigated. The rigidity-dependence ( $\sim P^{-0.7}$ ) of the ejecta-associated particle depression, and the reduction in the magnitude of the depression as ejecta move away from the Sun can be explained by a simple model in which particles diffuse across field lines into the ejecta. Examination of corotating decreases suggests that reduced diffusion in the trailing edges of corotating interaction regions produces such decreases. However the small dependence of the mean depression on the polarity of the solar magnetic field is not consistent with current models. Ion anisotropies at  $\sim 1$  MeV have been examined during solar particle events which commence when the observing spacecraft is inside an ejecta. In around 30% of such events, particles arrive first from the east of the Sun, opposite to the direction expected for flow along ideal spiral magnetic field lines but consistent with the presence in ejecta of looped field lines rooted at the Sun. Similar flows are rarely seen outside ejecta. Contributions have been made to work by E.W. Cliver (Phillips Laboratory) on the "extreme propagation" of solar energetic particles, where by solar particles are rapidly spread over  $\sim 300^\circ$  in helio longitude possibly by a coronal shock, and an investigation by J.F. Cooper (Hughes/STX) of the relationship between interplanetary particle anisotropies and intensity structures over the polar caps. Most of the above work will be reported on at the forthcoming ICRC, Solar Wind 8 and IAGA meetings. A paper on the association of electron bursts observed by the GSFC instrument on ISEE 3 in the geomagnetic tail with geomagnetic substorms is about to be submitted to JGR. A contribution was also made to a paper on the motion, structure and orientation of the magnetotail inferred from energetic ions (with C.J. Owen and J.A. Slavin, GSFC) recently published in JGR.

Future efforts will involve extending these analyses using the richness of the multi-spacecraft data sets. In particular, the various factors influencing the effectiveness of ejecta in producing cosmic ray depressions are still unclear, though it appears that in the subset of ejecta with flux-rope like magnetic fields, the magnetic field intensity is an important influence. Such efforts may provide a clear observational foundation for assessing the influence of ejecta (which is frequently neglected) in models of particle depressions. The energetic particle data may also be able to address issues such as the recent proposal by Gosling and co-workers that "open" field lines may exist in ejecta, connected to the interplanetary magnetic field.

## 2.2 X-ray Astronomy

Scientists associated with the University of Maryland currently conducting research in X-ray astronomy at NASA/Goddard Space Flight Center consist of Dr. Keith Arnaud, as an Assistant Research Scientist, and four graduate students: Damian Audley, Warren Focke, Andy Ptak, and

Jeonghee Rho. Two students successfully defended their theses during the past year and departed to take up postdoctoral positions, David Davis at the University of Alabama in Tuscaloosa and Takamitsu Miyaji at the Max Planck Institut für Extraterrestrische Physik. As usual, a number of other University of Maryland students worked with the X-ray group over the Summer.

Keith Arnaud has continued his work with ASCA (Advanced Satellite for Cosmology and Astrophysics). As part of the Guest Observer Facility he is responsible for software development and maintenance, for assisting in planning observations, for answering guest observer's questions, and ensuring that information flows from the hardware teams to the outside world. The XSPEC spectral fitting program that he maintains and improves continues to gain acceptance as the world standard in this field. On the science side

Keith Arnaud has published the first results from the ASCA observations of the Perseus cluster including 2-dimensional temperature and iron abundance maps. He has worked on the ASCA observations of Cygnus-A and has shown that there is indeed an obscured X-ray point source in the host galaxy of the radio source. This provides strong evidence for the unified scheme of radio sources which would say that if Cygnus-A was oriented closer to our line of sight then we would see it as a radio-loud quasar. In addition, Arnaud has worked on techniques for analyzing extended emission observed using ASCA. These methods take into account the energy- and position-dependent telescope spatial response.

Damian Audley's research under the supervision of Dr. Richard Kelley is in two main areas: X-ray astrophysics and cryogenic X-ray detector development. He has completed his spectroscopic and timing analysis of the BBXRT observation of the binary X-ray pulsar Centaurus X-3. This system consists of an accreting neutron star which orbits an O-type star every 2.1 days. The pulse period is  $\sim 4.8$  s and is decreasing due to accretion torques. A paper describing this work is in press with the ApJ. Audley has also worked on data from the EXOSAT observations of Cen X-3 provided by Dr. Vrilek at UMD. The data consist of pulse phase resolved spectra from various orbital phases. The pulse and orbital phase dependence of the iron emission will help reveal the structure of the emission region. In the lab Audley is continuing his work on microcalorimeters, which detect individual X-ray photons by converting their energy to heat. From the resulting temperature rise the photon energy can be found. Present day devices using ion-implanted thermistors as the temperature sensing element have achieved an energy resolution of  $\sim 7$  eV at 6 keV. However, because they are resistive devices, the resolution is degraded by Johnson noise. This can be eliminated by using a superconducting thermometer.

Another advantage of a superconducting thermometer is its lower heat capacity which leads to greater sensitivity. Audley is working on a thermometer whose thermometric property is the kinetic inductance of a superconducting stripline. If the film thicknesses are small compared to the penetration depth, the kinetic inductance is approximately proportional to the London penetration depth. Thus the kinetic inductance varies very rapidly with temperature close to the transition temperature. Audley has measured critical currents of titanium meander strips supplied by David Osterman at Hypres Inc. The critical current must be as large as possible for optimum resolution. Because of the problem of low critical currents it is possible that transition edge thermometers may provide a better way of increasing the resolution of microcalorimeters.

Warren Focke, with Dr. Jean Swank, has been investigating the black hole candidate Cygnus X-1

through analysis of X-ray light curves collected by the Japanese Ginga satellite. His attempts to extend shot noise models parameterizing the variability of this source have included not only the statistical properties of the data stream as a whole as used by previous researchers, but also modeling of the temporal form of individual events in the light curve by maximum likelihood fitting. This allows the study of distributions in single shot parameters and correlations between different parameters in a manner not possible with bulk statistical methods.

Jeonghee Rho, under the supervision of Dr. Rob Petre, has completed the analysis of the ROSAT PSPC X-ray observation of the supernova remnant 3C391 (G31.9+0.0). The PSPC image reveals centrally concentrated X-ray emission inside the radio shell, anticorrelated with the radio image. The northwestern half of the remnant has a strong radio shell and weak central X-ray emission. In contrast, the southeastern half has strong central X-ray emission and weak radio emission. Spectral analysis combining PSPC and Einstein Observatory IPC data shows that the emission is thermal, with a temperature of about five million degrees. The centrally concentrated morphology and the thermal origin of the X-ray emission along with the strong radio shell suggest 3C391 is similar to W44 and W28. There are large spectral variations between the northwestern and southeastern parts of the remnant: either the northwestern part has higher absorbing column or the southeastern part has a lower temperature. The PSPC data suggest the column density variation. Assuming constant temperature across the remnant, the difference in column is large enough to state that the low X-ray surface brightness in the northwestern part is due to the absorption. The X-ray data of 3C391 are consistent with the idea that the progenitor supernova has exploded just inside a molecular cloud. The northwestern structure is created by the propagation of the SN shock into the cloud, and the enhanced central X-ray emission arises from evaporation of clumps from the molecular cloud. The southeastern radio and X-ray emission represents a "breakout" from the northwestern main shell.

Andy Ptak has worked with Dr. Peter Serlemitsos and Dr. Tahir Yaqoob on ASCA data of nearby spiral galaxies. This includes specifically NGC 3628 (Yaqoob, et al., submitted) which contains one of the flattest spectra observed to date in a non-AGN galaxy, and NGC 3147 (Ptak, et al., to be submitted shortly), recently reclassified as a low-luminosity Seyfert 2. The analysis of the NGC 3147 data, which contain a (possibly complex) Fe line, entailed some modelling of the spectra of obscured AGN. He has performed preliminary analysis of other galaxies, some of which are LINERS, whose typical spectrum is unabsorbed, with a hard component ( $\gamma = \sim 1.5 - 2$  or  $kT \sim 6-7$  keV) and occasionally a soft component with  $kT < 0.5 - \sim 1$  keV. Ptak has also worked on miscellaneous such as generating a best-guess Astro-E response and examining the ASCA PSF.

### 2.3 Low Energy Gamma-Ray Astronomy

The main focus of this research is high resolution gamma-ray spectroscopy of celestial source in the 20 keV to 10 MeV energy range. The principle experimental objective of this program is to search for and study narrow lines in the low-energy gamma-ray spectrum. Such lines can be produced by 1) cosmic ray induced emission from nuclear excited states, 2) remnant radioactivity from nucleosynthesis, 3) positron annihilation, and 4) cyclotron line emission from the strong magnetic field regions near the poles of a neutron star. Observational evidence exists at present for processes 2), 3), and 4). The technique of nuclear spectroscopy applied to astrophysics promises to be a powerful new diagnostic tool for probing high-energy astrophysical processes such as are known to exist in the vicinity of neutron stars and black holes. This is a young field, but already results are in hand that conclusively demonstrate the potency of the method. The principle experimental activity within this

program is the development and operation of balloon- and satellite-borne instrumentation that perform high-resolution gamma-ray spectroscopy using Germanium detectors. In addition, ground based optical instrumentation is being developed to support the balloon and satellite observations. The individual programs are described briefly as follows:

### 2.3.1 Gamma-Ray Imaging Spectrometer (GRIS)

GRIS is a very sophisticated and powerful gamma-ray telescope that is carried above the earth's atmosphere on high altitude balloons. The basic experiment consists of an array of seven large high-purity Germanium detectors to make precise measurements ( $E/\Delta E \sim 500$ ) of gamma-ray energies in the 20 keV to 10 MeV range. The detector array is surrounded by a thick massive anti-coincidence shield to suppress the strong atmospheric and instrumental gamma-ray background flux. In addition there is an active NaI coded-aperture mask that will produce gamma-ray images over a  $9^\circ \times 15^\circ$  field of view. GRIS measures gamma-ray fluxes that are five to ten times weaker than could be detected by the best previous instruments. GRIS was first flown successfully in 1988 from Alice Springs, Australia. Exciting new results were obtained on the Galactic Center arc SN 1987. It will be flown 1 - 2 times yearly over the next 5 - 6 years.

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The TGRS is an already existing satellite-borne gamma-ray spectrometer intended to perform high resolution studies of the spectra of gamma-ray bursts. It is planned for flight on the WIND spacecraft that is part of the Global Geospace System (GGS), a new multiple-spacecraft mission to be launched. Its primary purpose is to make the first precise detailed studies of the lines that are known to exist in the spectra of gamma-ray bursts. Two kinds of lines have been observed. First, lines in the vicinity of 50 keV occur in many bursts. They are believed to result from electron cyclotron emission in the enormous magnetic fields ( $10^{12}$ ) gauss that are typically present at the poles of neutron stars. Second, lines in the vicinity of 400 keV have been observed in 10% of the bursts. These are believed to be due to electron-positron annihilation (511 keV) radiation produced near the surface of a neutron star. This radiation is subsequently redshifted as it escapes the strong neutron star gravitational field. If this is true then it represents the first direct measurement of the gravitational potential of a neutron star. The basic instrument consists of a single Germanium crystal radiatively cooled to a temperature of 95K. The detector is unshielded and nearly omnidirectional as the gamma-ray burst may come from any random direction in the sky. It will make spectral measurements with typically 40 times better energy resolution than the best previous instrument.

### 2.3.3 Rapidly Moving Telescope (RMT)

RMT is a ground based optical telescope capable of slewing to any target on the sky in less than one second, tracking the target with sub-arcsecond stability, and imaging it with one arcsecond resolution. It can see objects as faint as 15-th magnitude with one second exposures. Its purpose is to locate and identify the optical counterpart flash to Gamma Ray Burst events. It will operate in conjunction with the MIT Explosive Transient Camera. The RMT instrument is able to move so quickly, because unlike a traditional telescope, only the mirror assembly moves (an azimuth-elevation mechanism); thereby picking out a patch of the night sky and reflecting it into a fixed telescope. Imaging is done with a CCD camera. The instrument is designed to operate totally automated. The observing program and data analysis is all computer controlled. Currently the instrument is undergoing integration and



shakedown operation at Kitt Peak. First sky observations occurred in 1991.

### 2.3.4 Gamma-Ray Astronomy

The EGRET instrument on the Compton Gamma Ray Observatory covers the energy range from about 20 MeV to 30 GeV and has made a number of significant discoveries in both galactic and extra-galactic gamma ray astronomy. These include the measurement of the high energy gamma ray emission properties from pulsars, quasars, and BL Lac objects. Observations of gamma ray burst have led to the discovery of surprising aspects of these mysterious events. A detailed study of the galactic diffuse radiation to study the galactic cosmic ray distribution and galactic dynamics is also in progress.

To continue these advances, the Advanced Gamma-ray Astronomy Telescope Experiment (AGATE) is currently being designed. This will be a larger "2m-class" instrument with increased sensitivity and angular resolution. Large area, 2m x 2m drift changers are being developed for the imaging detector, large area anti-coincidence, coincidence and energy measuring systems will be required to complete the design of this instrument.

Summer research opportunities and Ph.D. thesis possibilities exist for students interested in these areas.

## 2.4 Theoretical Astrophysics

Theoretical studies are essential in order to determine the most important directions to pursue in future measurements, the interpretation of existing observations within a self-consistent framework, and in the development of new experimental techniques. Theoretical research is pursued in X-, gamma- and cosmic ray astrophysics, as well in extragalactic astronomy, cosmology, compact object astrophysics, and solar physics.

The theory group presently supports two graduate students doing thesis research at Goddard Space Flight Center.

Yuan-Kuen Ko, working with Dr. Tim Kallman, completed her thesis work last summer. She studied the effects of X-ray irradiation on the structure and dynamics of accretion disks in galactic X-ray binary sources.

Ramin Sina is working with Dr. Alice Harding on a thesis project involving the investigation of processes in strong magnetic fields and their application to radiation from neutron stars. This past year, Sina completed an analytic calculation of the Trident production and electron-positron scattering cross sections and has begun to evaluate the cross sections numerically for a range of parameters. Preliminary results were presented in April at the APS Spring Meeting in Washington.

## 3. Future Efforts

Many of the projects described previously are ongoing and work will continue in the investigation of the relevant phenomena. Some more specific details are given below.

### 3.1.1 Cosmic Ray Detections

1994-1995

## **2. Proposed Joint Effort of the University of Maryland and the NASA Goddard Space Flight Center Laboratory for High Energy Astrophysics**

This grant supports activities conducted by University personnel both on campus and at the Goddard Space Flight Center. Work will be concentrated in the following areas:

- 1) Detection of cosmic rays and studies of the solar modulation of galactic cosmic rays
- 2) Research with several past and upcoming X-ray satellites
- 3) High resolution gamma-ray spectroscopy of celestial sources
- 4) Theoretical astrophysics

This section describes the work accomplished to date and the proposed joint effort for the next grant period for each of these areas within the overall research program. During the upcoming year, we propose to continue our joint efforts in the areas listed above.

### **2.1 Cosmic Rays**

Cosmic rays are the only samples of matter which reach earth from outside the solar system. As such, they carry information on their origin, acceleration, and subsequent propagation.

#### **2.1.1 Cosmic Ray Detection**

Between the present low energy antiproton measurements, which extend up to about 1 GeV and the higher energy measurements of Golden (around 5 GeV) there are no antiproton measurements except those of Bogomolov, which have error bars extending over an order of magnitude. In the summer of 1992, we flew the Isotope Matter Antimatter Experiment (IMAX) which took data on antiproton fluxes from 100 MeV to about 3 GeV. The experiment utilized the NASA Balloon Borne Magnet Facility (BBMF). Analysis of this data is ongoing.

Another experiment in which this group is involved is the MASS (MATTER-Antimatter Spectrometer experiment, which had a flight in the fall of 1992. This experiment has taken data on antiprotons in the 5 - 10 GeV range, as well as making positron measurements up to about 20 GeV.

#### **2.1.2 Low Energy Cosmic Rays**

Ian Richardson has undertaken further work using energetic charged particle data from the NASA/Goddard Space Flight Center instruments on IMP 8, ISEE 3/ICE, and Helios 1 and 2.

Recent studies, in collaboration with H. V. Cane (University of Tasmania), G. Wibberenz (University of Kiel), and T. T. von Rosenvinge (GSFC), have focussed on the use of high energy ( $> 60$  MeV) proton data from IMP 8 and Helios 1 and 2 to understand cosmic ray decreases associated with interplanetary shocks, ejecta (material ejected during coronal mass ejections at the Sun), and corotating high-speed solar wind streams. Because these spacecraft data do not suffer the diurnal variations observed by ground-based neutron monitors, the decreases can be related accurately to solar wind structures passing the spacecraft, while the use of more than one spacecraft allows a particular decrease to be observed at a range of heliolongitudes and heliocentric distances. Conflicting results on the relative role of the post-shock turbulence and the ejecta forming the shock driver in the production of cosmic ray decreases have been inferred from previous studies using neutron monitor data. Our observations show conclusively that both play a role. However, the shock produces a decrease extending over several days with a relatively smooth decline and recovery whereas the ejecta produces a more localized decrease, with more abrupt changes in the particle flux at the ejecta boundaries. The depth of the depression depends principally on whether the ejecta is encountered, the longitude of the spacecraft relative to the solar event producing the shock, and the heliocentric distance. Since the rapid decrease characteristic of "Forbush decreases" is only observed when the ejecta is encountered, models of FDs in which the decrease is produced only by the post-shock turbulence must be modified to include the effect of the ejecta. A paper on preliminary observations was presented at the 23rd. Int. Cosmic Ray Conf. (Vol. 3, 294) and a more extended manuscript has been submitted to J. Geophys. Res.

Other papers on multi-spacecraft observations of decreases associated with corotating high-speed streams, and on the association of decreases with ejecta, are in the final stages of preparation. We identify the ejecta principally from depressions in the solar wind plasma temperature below that expected for "normal" solar wind expansion. The ejecta occurrence rate shows a good correlation with solar activity and with the CME rate observed by spacecraft coronagraphs. Since plasma temperature data are available back to 1965, this technique allows the ejecta/CME rate to be inferred for a period starting before the beginning of routine coronagraph observations in the mid-1970's. We suggest that some features of the long-term modulation of cosmic rays may result from changes in the CME rate as well as from the effects of particle drifts. This work will be reported at the Spring American Geophysical Union meeting in May.

A paper has also been submitted to J. Geophys. Res. (in conjunction with C. J. Owen and J. A. Slavin of LEP/GSFC) on the structure of the plasma sheet in the deep geomagnetic tail inferred from ISEE 3 energetic particle anisotropies at the

plasma sheet boundary layer.

Richardson has also acted as a reviewer of the International Halley Watch CD-ROM Archive of data from the spacecraft encounters with comets P/Halley and P/Giacobini-Zinner on behalf of the Small Bodies Node of the Planetary Data System at the University of Maryland.

Papers published include a survey of energetic electron bursts observed by ISEE 3 in the geomagnetic tail (J. Geophys. Res., 98, 13441, 1993), an IMP 8 study of cosmic ray decreases (J. Geophys. Res., 98, 13295, 1993), a study of shock driver signatures (J. Geophys. Res., 98, 15295, 1993), a case study of energetic particle propagation in a magnetic cloud (J. Geophys. Res., 98, 15497), a survey of bidirectional particle flows at the Helios 1 and 2 spacecraft (Ap. J., 420, 926, 1994), and a study of the relationship between solar and interplanetary phenomena in August 1989 using ICE and IMP 8 observations (J. Geophys. Res., 99, 2513, 1994). Also, four contributed papers appeared in the proceedings of the 23rd. Int. Cosmic Ray Conf. (v. 3, p. 226; v. 3, p. 230; v. 3, p. 282; v. 3, p. 294).

## 2.2 X-ray Astronomy

Scientists associated with the University of Maryland currently conducting research in X-ray astronomy at NASA/Goddard Space Flight Center consist of Keith Arnaud, as an Assistant Research Scientist, and five graduate students: Damian Audley, Warren Focke, Takamitsu Miyaji, Jeonghee Rho, and Kim Weaver. In addition, Andy Ptak and Yanga Fernandez, while not yet doing full-time research have worked with members of the X-ray group during the last year. Ptak has been analyzing ASCA data on AGN with Dr. Peter Serlemitsos and Dr. Tahir Yaqoob while Fernandez has been working with Arnaud on the ASCA observation of the cluster Abell 2218. As usual, a number of other University of Maryland students worked with the X-ray group over the Summer.

Keith Arnaud has spent the last year working on the ASCA (Advanced Satellite for Cosmology and Astrophysics). This included a two month summer visit to ISAS (Tokyo) to get the data analysis software up to speed and to start work on some of the performance verification phase observations. Preliminary results are now being written up as letters to be published in special issues of the PASJ and ApJ. These results include the first 2-D temperature and iron abundance map of the Perseus cluster showing departures from azimuthal symmetry. Travelling due West from the cluster center the temperature rises from 4 keV to 9 keV then quite suddenly drops back to 5 keV. This is hard to explain using any static model and throws doubt on current methods used to calculate the gravitating mass of clusters. Another result giving us cause for thought has been the ability of cooling flow models to correctly predict the detailed spectra of the center of

several clusters. These problems appear to be a combination of an incorrect physical model and inaccuracy in the atomic physics used in the plasma codes. Arnaud has also given several graduate level lectures as part of the X-ray astronomy course being taught by Dr. Saeqa Vrtilek (UMd).

Damian Audley's research under the supervision of Dr. Richard Kelley is in two main areas: X-ray astrophysics and cryogenic X-ray detector development. He has performed spectroscopic and timing analysis of the BBXRT observation of the binary X-ray pulsar Centaurus X-3. He resolved the Fe K-alpha emission into two components: a narrow line at 6.4 keV corresponding to fluorescence of relatively cold material close to the accretion disc, and a stronger broad line at 6.7 keV which is emitted by H- and He-like iron. This is due to reprocessing of X-ray radiation in the extended, highly ionized stellar wind of the O-type star. He measured the width of this broad line for the first time and found that it is not consistent with a single line from the ionized stellar wind. Audley presented these results at the AAS meeting in Berkeley in June 1993. In the lab Audley is investigating superconducting kinetic inductance thermometers to find out whether these can be used to improve the spectral resolution of the microcalorimeters. The initial results showing good agreement with theoretical predictions were presented at the LTD-5 conference in Berkeley in August 1993.

David Davis has been continuing his work on the X-ray structures of clusters of galaxies under the supervision of Dr. Richard Mushotzky. At the summer AAS meeting he presented the results of ROSAT observations of Butcher-Oemler clusters. He has submitted two papers to ApJ comparing X-ray and optical observations of A548 (Davis et al.) and A2151 Bird, Davis & Beers). A paper on the NGC 4261 group of galaxies is in the final stages of preparation. This is a follow-up to last year's much publicized work on NGC 2300 and shows that the extensive hot gas found in that case is not an isolated example. Davis passed on some of his hard-won technical expertise at the ROSAT Science Symposium with a presentation on subtracting background for extended sources.

Warren Foche is studying the accretion disk dynamics. Under the guidance of Dr. Jean Swank he is studying the relation between X-ray light curves and Cygnus X-1 in different energy bands. He is currently using data collected by EXOSAT and Ginga, but hopes to get more data for this source and other galactic black hole candidates soon.

Takamitsu Miyaji, with Ofer Lahav (IoA), Keith Jahoda, and Elihu Bold (LHEA) has been investigating the cross correlation between surface brightness of the cosmic X-ray background and the number counts of 60 micron flux limited IRAS sample. With a detailed modelling and Monte-Carlo simulations, he found that the

detected correlation signal is consistent with a model that the local X-ray volume emissivity is dominated by AGNs with  $L_x > 10^{42} \text{ergs}^{-1}$ . A paper on this topic has recently been accepted to ApJ. His other ongoing projects include investigating the clustering property of AGNs calculating spatial cross-correlation functions between X-ray selected AGNs and IRAS/Optical galaxies. He is also actively analyzing the ROSAT PSPC data on the three fields in the supercluster BB18 with an intention to find or set an upper limit to the X-ray emission from intercluster hot gas.

Jeonghee Rho is studying with Dr. Rob Petre the X-ray emission from composite SNRs in order to understand the origin of their X-ray emission and the way that the ISM structure affects the morphology and evolution of the SNR. Despite their X-ray morphological similarity to the plerions and concerted efforts to place some of these in the plerionic class, all existing X-ray spectral evidence suggests that the X-ray emission is thermal for this class of remnants. Rho has an ApJ paper in press on the ROSAT, H $\alpha$  and [S II] observations of the supernova remnant W 44. She presented ROSAT PSPC observations CTB 109 (G109.1-1.0) and IC 443 at the conferences "Workshop on Supernova Remnants and The Physics of Strong Shock Waves" at North Carolina, "ROSAT Science Symposium and Data Analysis Workshop" at Maryland and 94 AAS meeting. Her other main projects are the ROSAT PSPC observations of W28 and five composite SNR in LMC. In addition she is comparing BBXRT and HRI observations of IC 443 with optical data in order to test the non-equilibrium ionization and evaporation model.

Kim Weaver successfully defended her thesis and has taken a postdoctoral position at Penn. State to work on ASCA data.

### 2.3 Low Energy Gamma-Ray Astronomy

The main focus of this research is high resolution gamma-ray spectroscopy of celestial sources in the 20 keV to 10 MeV energy range. The principle experimental objective of this program is to search for and study narrow lines in the low-energy gamma-ray spectrum. Such lines can be produced by 1) cosmic ray induced emission from nuclear excited states, 2) remnant radioactivity from nucleosynthesis, 3) positron annihilation, and 4) cyclotron line emission from the strong magnetic field regions near the poles of a neutron star. Observational evidence exists at present for processes 2), 3), and 4). The technique of nuclear spectroscopy applied to astrophysics promises to be a powerful new diagnostic tool for probing high-energy astrophysical processes such as are known to exist in the vicinity of neutron stars and black holes. This is a young field, but already results are in hand that conclusively demonstrate the potency of the method. The principle experimental activity within this program is the development and operation of balloon- and satellite-borne instrumentation that perform high-resolution

gamma-ray spectroscopy using Germanium detectors. In addition, ground based optical instrumentation is being developed to support the balloon and satellite observations. The individual programs are described briefly as follows:

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GRIS is a very sophisticated and powerful gamma-ray telescope that is carried above the earth's atmosphere on high altitude balloons. The basic experiment consists of an array of seven large high-purity Germanium detectors to make precise measurements ( $E/E \sim 500$ ) of gamma-ray energies in the 20 keV to 10 MeV range. The detector array is surrounded by a thick massive anti-coincidence shield to suppress the strong atmospheric and instrumental gamma-ray background flux. In addition there is an active NaI coded-aperture mask that will produce gamma-ray images over a  $9^\circ \times 15^\circ$  field of view. GRIS measures gamma-ray fluxes that are five to ten times weaker than could be detected by the best previous instruments. GRIS was first flown successfully in 1988 from Alice Springs, Australia. Exciting new results were obtained on the Galactic Center arc SN 1987. It will be flown 1 - 2 times yearly over the next 5 - 6 years.

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The TGRS is an already existing satellite-borne gamma-ray spectrometer intended to perform high resolution studies of the spectra of gamma-ray bursts. It is planned for flight on the WIND spacecraft that is part of the Global Geospace System (GGS), a new multiple-spacecraft mission to be launched. Its primary purpose is to make the first precise detailed studies of the lines that are known to exist in the spectra of gamma-ray bursts. Two kinds of lines have been observed. First, lines in the vicinity of 50 keV occur in many bursts. They are believed to result from electron cyclotron emission in the enormous magnetic fields ( $10^{12}$ ) gauss that are typically present at the poles of neutron stars. Second, lines in the vicinity of 400 keV have been observed in 10% of the bursts. These are believed to be due to electron-positron annihilation (511 keV) radiation produced near the surface of a neutron star. This radiation is subsequently redshifted as it escapes the strong neutron star gravitational field. If this is true then it represents the first direct measurement of the gravitational potential of a neutron star. The basic instrument consists of a single Germanium crystal radiatively cooled to a temperature of 95K. The detector is unshielded and nearly omnidirectional as the gamma-ray burst may come from any random direction in the sky. It will make spectral measurements with typically 40 times better energy resolution than the best previous instrument.

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### 3. Future Efforts

Many of the projects described previously are ongoing and work will continue in the investigation of the relevant phenomena. Some more specific details are given below.

#### 3.1.1 Cosmic Ray Detections

Some of the most significant questions in the field of particle astrophysics can be addressed by measurements of the isotopic composition of the cosmic radiation. The radioactive clock isotope  $^{10}\text{Be}$ , with a half-life of  $1.5 \times 10^6$  years, is a particularly important case. Measurements of the abundance of this isotopes to relativistic energies, where time dilation effects become appreciable, will probe the density distribution of interstellar matter in the volume in which cosmic rays propagate. The Isotope Magnet Experiment (ISOMAX) is being planned by the High Energy Cosmic Ray Group. This instrument will use a superconducting magnet and drift chamber tracking to measure the magnetic rigidity of incident cosmic rays. Combined with precision velocity measuring devices (time-of-flight, aerogel Cherenkov) the instrument will be capable of determining the mass of light isotopes well into the relativistic. Development work on this instrument is just beginning. We anticipate that in the next stage of development, a University of Maryland graduate student will join the project.

#### 3.1.2 Low Energy Cosmic Rays

Ian Richardson will continue his study of the charged particle anisotropy data base from the NASA/Goddard Space Flight Center Medium Energy Cosmic Ray Experiment in the ISEE-3/ICE spacecraft. Many of the other projects will continue including the investigations into the origins of ions trapped within closed solar wind magnetic field regions as well as the study of ion

1993-1994

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- 2) Support work for several past and upcoming X-ray satellites
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This section describes the work accomplished to date and the proposed joint effort for the next grant period for each of these areas within the overall research program. During the upcoming year, we propose to continue our joint efforts in the areas listed above.

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Between the present low energy antiproton measurements, which extend up to about 1 GeV and the higher energy measurements of Golden (around 5 GeV) there are no antiproton measurements except those of Bogomolov, which have error bars extending over an order of magnitude. In the summer of 1992, we flew the Isotope Matter Antimatter Experiment (IMAX) which took data on antiproton fluxes from 100 MeV to about 3 GeV. The experiment utilized the NASA Balloon Borne Magnet Facility (BBMF).

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#### 2.1.2 Low Energy Cosmic Rays

Ian Richardson has continued to undertake various studies using the comprehensive data base of charged particle data from the NASA/Goddard Space Flight Center experiments on ISEE-3/ICE, IMP-8, and Helios-1 and -2.

Study of bidirectional ion flows (BIFs) has continued. A

paper on BIFs observed by the IMP-8 and ISEE-3/ICE spacecraft has been published in *Astrophys. J. (Suppl.)* (April 1993) and a further paper, on Helios 1 and 2 observations, submitted to *Astrophys. J.* The association of BIFs with various solar wind structures is discussed in the latter paper. It is found that around one third of BIFs occur in shock drivers, some 20% in non-compressive density enhancements, and the others in various solar wind regions such as corotating high-speed streams, corotating interaction regions, and upstream of shocks. Thus although some BIFs are clearly associated with the passage of material from coronal mass ejections (CMEs) apparently containing closed or looped magnetic field lines, there is not an exclusive association. In particular, there is evidence that some post-shock BIFs are not associated with shock driver entry but may occur on open field lines connected to the shock. In a related study in conjunction with H.V. Cane (GSFC/University of Tasmania) (to appear in *J. Geophys. Res.*), the relationship of the presence of post-shock driver signatures in solar wind plasma, magnetic field and particle data to the location of the solar event initiating the shock is discussed. The general absence of such signatures following shocks from events further than 50° from the spacecraft heliolongitude suggests that shock drivers typically extend up to ~50° from the source. Again there are some shocks (principally from far eastern sources) which are followed by bi-directional ion streaming on field lines outside of the driver but connected to the shock. Aspects of this work will be reported at the AGU meeting in Baltimore (May 1993) and at the Int. Cosmic Ray Conf. in Calgary (July 1993).

Two papers have been written with C.J. Farugia (GSFC/LEP) on BIFS in individual magnetic clouds. The first (*J. Geophys. Res.*, May 1993) includes discussion of a solar particle injection into a magnetic cloud which suggests that magnetic field lines in the cloud were still rooted at the Sun. The second (submitted to *J. Geophys. Res.*) considers particle observations at IMP-8 (in the Earth's tail lobe and magnetosheath) and ISEE-3 (at the upstream libration point) during the encounter of a magnetic cloud with magnetosphere. Following a solar event which occurs close to the time at which the magnetic cloud encounters the Earth, the arrival times of particles inside and outside the cloud are consistent with the considerably longer path-length along spiral flux-rope-like magnetic field lines within the magnetic cloud predicted by the magnetic field observations. The particle flows in the magnetosphere indicate the entry of these particles via the cloud magnetic field lines which in turn are apparently rooted at the Sun.

A paper (with Daniel Winterhalter, JPL) on ICE spacecraft observations off the west limb of the Sun in 1989 will be presented at the Int. Cosmic Ray Conf. Although the spacecraft data are intermittent, we have studied the association between CMEs observed by the SMM spacecraft in August 1989 and signatures

of the passage of CME material at ICE a few days later.

The relationship of shocks and shock drivers to cosmic ray decreases and low energy particle acceleration has been discussed in a paper (to appear in J. Geophys. Res.) with H.V. Cane and T.T. von Rosenvinge (GSFC). It is argued that low energy particle observations may provide useful information on solar wind structures (such as shocks) remote from the spacecraft (which does not therefore encounter the structure) which may modulate the cosmic ray flux.

The structure of the geomagnetic tail has been investigated (with J.A. Slavin and C.J. Owen GSFC/LEP) in a paper (to appear in J. Geophys. Res.) describing the first survey of data from the GSFC experiment on ISEE-3 during the spacecraft's excursion into the deep geomagnetic tail in 1982-3. Brief (< 30 min duration) bursts of 0.2-2 MeV electrons are observed, predominantly in the plasma sheet on closed field lines connected to the Earth. The near absence of such events beyond 80  $R_E$  downtail provides evidence of predominantly open rather than closed magnetic structures in the plasma sheet beyond this distance downtail, completely consistent with evidence of a neutral line at this distance downtail found previously in studies of ISEE-3 plasma, magnetic field and energetic ion data. The bursts also appear to be associated with substorm onsets though further study of this topic is continuing.

Papers have also been published on diffusion coefficients of energetic water group ions near comet Giacobini-Zinner (in collaboration with L.C. Tan (U. of MD/Dept. of Physics) (J. Geophys. Res., March, 1993) and on corotating MeV/amu ion enhancements at  $\leq 1$  AU from 1978 to 1986 (J. Geophys. Res., January 1993).

## 2.2 X-ray Astronomy

Scientists associated with the University of Maryland currently conducting research in X-ray astronomy at NASA/Goddard Space Flight Center consist of Keith Arnaud, as an Assistant Research Scientist, and seven graduate students: Damian Audley, Damian Christian, David Davis, Warren Focke, Takamitsu Miyaji, Jeonghee Rho, and Kim Weaver. In addition, a number of University of Maryland students worked with the X-Ray group over the Summer.

Keith Arnaud has spent the last year commuting between GSFC, ISAS (Tokyo) and IoA (Cambridge, UK) in preparation for the Astro-D mission. This was successfully launched on Feb. 20, 1993 from Kagoshima Space Center in southern Japan. Once in orbit it was renamed ASCA (Advanced Satellite for Cosmology and Astrophysics). Arnaud is already at work analyzing data and writing and testing software for this ground-breaking mission.

Preliminary analysis indicates that the telescopes and instruments are working as expected and exciting data is being collected. In his spare moments Arnaud has continued his analysis of BBXRT and ROSAT data. Of particular interest is the ROSAT PSPC observation of the cluster A1795. This very long exposure shows the cluster to be isothermal out to more than one Mpc but with a cool region in the inner 100 kpc. This cool region also shows excess absorption, thus confirming the results obtained using the Einstein Observatory SSS.

Damian Audley has been working with Richard Kelley, both on hardware and data analysis. In the lab he has been testing kinetic inductors as part of a project to build a quantum calorimeter which uses a kinetic inductor rather than a thermistor as a temperature sensor. Since the kinetic inductor is superconducting this will improve the calorimeter resolution significantly. Damian has also been analyzing the BBXRT observation of Centaurus X-3, a binary X-ray pulsar. These data show the previously unresolved iron line to consist of a broad line at 6.7 keV and possibly a narrow line at 6.4 keV. The 6.7 keV line intensity appears to be varying out of phase with the continuum.

Damian Christian has completed his degree under the supervision of Jean Swank. His thesis is entitled "Spectral and Temporal Behaviour of Low Mass X-Ray Binaries Observed with the Einstein SSS and MPC, and the Broad Band X-Ray Telescope". His thesis used simultaneous observations of 50 LMXRBs obtained by the Einstein SSS (0.5-4.5 keV) and MPC (1.0-20.0 keV and several observations from BBXRT. Christian showed the X-ray continua of these sources to be generally complex, requiring combinations of thermal bremsstrahlung and blackbody spectra or optically thick disk models for the bright Z sources and power-law models for the bursters. He confirmed the strongest of the previous reports of lines due to O VIII or Fe L transitions. In particular, X0614+091 was found to have a large emission feature at an energy consistent with that of O VIII, showing that a relatively low luminosity disk accretor can have a disk corona.

In between newspaper interviews David Davis has been continuing his work on the X-ray structures of clusters of galaxies under the supervision of Richard Mushotzky. His paper with Mushotzky on the substructure in the Coma and A2256 clusters has been published in Ap.J. Davis provided the highlight of the January AAS meeting when his work with Mulchaey (UMd), Mushotzky, and Burstein (ASU) was presented. A ROSAT PSPC image of the very poor group of galaxies around NGC 2300 showed extensive hot gas. The only way that this gas can be contained in the group is if the mass to light ratio of the group is  $\sim 25$ . This large a fraction of dark matter has never been seen before and is the amount required to close the universe (and predicted by most inflationary cosmology models).

Warren Focke is studying the dynamics of accretion disks. With Jean Swank he is attempting to model the time lags between low and high energy X-ray lightcurves observed in Cygnus X-1. This project will be expanded to other sources believed to consist of accretion disks around black holes of approximately stellar mass.

Takamitsu Miyaji is working with Elihu Boldt on a number of projects relating to clusters of galaxies and the large scale structure of the universe. He has submitted a paper (to Ap.J.) describing the results of the BBXRT observation of the cluster A2256. This work measured the gravitating mass of the cluster and showed the existence of spectral features consistent with the shockwaves caused by the merger of two clusters, believed to be occurring in A2256. Miyaji is also measuring the correlation between the X-ray background (XRB) surface brightness, as determined by the HEAO-1 A2 experiment, and the IRAS galaxies. This will provide an estimate of the contribution of local galaxies to the XRB.

Jeonghee Rho is working with Rob Petre on a study of the X-ray emission from composite SNRs. She has analyzed ROSAT PSPC observations of W44 and presented the results at the AAS and the "Back to the Galaxy" conference. Rho is also working on IC443 using ROSAT (PSPC and HRI), BBXRT, and shortly, ASCA observations. The results will be presented at an IAU meeting this summer. Her thesis will consist of a study of the X-ray morphologies and spectra of a sample of 30 Galactic SNR and 6 SNR in the LMC.

Kim Weaver is in the final stages of her thesis under the guidance of Richard Mushotzky and Andrew Wilson (UMd). She has published (in Ap.J.) the BBXRT results on the Fe K emission line feature in the Seyfert I galaxy NGC 4151. This paper showed that, contrary to previous assumptions, the Fe K emission line is narrow and cannot come from the inner regions of the accretion disk around a massive black hole, but instead is probably produced in the Broad Line Region. A second paper on NGC 4151, to be submitted this month, demonstrates that the conventional wisdom about the spectrum of the low energy X-rays is also wrong and that the source must be more complicated than assumed heretofore.

### 2.3 Low Energy Gamma-Ray Astronomy

The main focus of this research is high resolution gamma-ray spectroscopy of celestial sources in the 20 keV to 10 MeV energy range. The principle experimental objective of this program is to search for and study narrow lines in the low-energy gamma-ray spectrum. Such lines can be produced by 1) cosmic ray induced emission from nuclear excited states, 2) remnant radioactivity from nucleosynthesis, 3) positron annihilation, and 4) cyclotron

line emission from the strong magnetic field regions near the poles of a neutron star. Observational evidence exists at present for processes 2), 3), and 4). The technique of nuclear spectroscopy applied to astrophysics promises to be a powerful new diagnostic tool for probing high-energy astrophysical processes such as are known to exist in the vicinity of neutron stars and black holes. This is a young field, but already results are in hand that conclusively demonstrate the potency of the method. The principle experimental activity within this program is the development and operation of balloon- and satellite-borne instrumentation that perform high-resolution gamma-ray spectroscopy using Germanium detectors. In addition, ground based optical instrumentation is being developed to support the balloon and satellite observations. The individual programs are described briefly as follows:

#### 2.3.1 Gamma-Ray Imaging Spectrometer (GRIS)

GRIS is a very sophisticated and powerful gamma-ray telescope that is carried above the earth's atmosphere on high altitude balloons. The basic experiment consists of an array of seven large high-purity Germanium detectors to make precise measurements ( $E/\Delta E \sim 500$ ) of gamma-ray energies in the 20 keV to 10 MeV range. The detector array is surrounded by a thick massive anti-coincidence shield to suppress the strong atmospheric and instrumental gamma-ray background flux. In addition there is an active NaI coded-aperture mask that will produce gamma-ray images over a  $9^\circ \times 15^\circ$  field of view. GRIS measures gamma-ray fluxes that are five to ten times weaker than could be detected by the best previous instruments. GRIS was first flown successfully in 1988 from Alice Springs, Australia. Exciting new results were obtained on the Galactic Center arc SN 1987. It will be flown 1 - 2 times yearly over the next 5 - 6 years.

#### 2.3.2 Transient Gamma-Ray Spectrometer (TGRS)

The TGRS is a satellite-borne gamma-ray spectrometer intended to perform high resolution studies of the spectra of gamma-ray bursts. It is planned for flight on the WIND spacecraft that is part of the Global Geospace System (GGS), a new multiple-spacecraft mission to be launched. Its primary purpose is to make the first precise detailed studies of the lines that are known to exist in the spectra of gamma-ray bursts. Two kinds of lines have been observed. First, lines in the vicinity of 50 keV occur in many bursts. They are believed to result from electron cyclotron emission in the enormous magnetic fields ( $10^{12}$ ) gauss that are typically present at the poles of neutron stars. Second, lines in the vicinity of 400 keV have been observed in 10% of the bursts. These are believed to be due to electron-positron annihilation (511 keV) radiation produced near the surface of a neutron star. This radiation is subsequently redshifted as it escapes the strong neutron star

gravitational field. If this is true then it represents the first direct measurement of the gravitational potential of a neutron star. The basic instrument consists of a single Germanium crystal radiatively cooled to a temperature of 95K. The detector is unshielded and nearly omnidirectional as the gamma-ray burst may come from any random direction in the sky. It will make spectral measurements with typically 40 times better energy resolution than the best previous instrument.

### 2.3.3 Rapidly Moving Telescope (RMT)

RMT is a ground based optical telescope capable of slewing to any target on the sky in less than one second, tracking the target with sub-arcsecond stability, and imaging it with one arcsecond resolution. It can see objects as faint as 15-th magnitude with one second exposures. Its purpose is to locate and identify the optical counterpart flash to Gamma Ray Burst events. It will operate in conjunction with the MIT Explosive Transient Camera. The RMT instrument is able to move so quickly, because unlike a traditional telescope, only the mirror assembly moves (an azimuth-elevation mechanism); thereby picking out a patch of the night sky and reflecting it into a fixed telescope. Imaging is done with a CCD camera. The instrument is designed to operate totally automated. The observing program and data analysis is all computer controlled. Currently the instrument is undergoing integration and shakedown operation at Kitt Peak. First sky observations occurred in 1991.

### 2.3.4 Gamma-Ray Astronomy

The EGRET instrument on the Compton Gamma Ray Observatory covers the energy range from about 20 MeV to 30 GeV and has made a number of significant discoveries in both galactic and extra-galactic gamma ray astronomy. These include the measurement of the high energy gamma ray emission properties from pulsars, quasars, and BL Lac objects. Observations of gamma ray bursts have led to the discovery of surprising aspects of these mysterious events. A detailed study of the galactic diffuse radiation to study the galactic cosmic ray distribution and galactic dynamics is also in progress.

To continue these advances, the Advanced Gamma-ray Astronomy Telescope Experiment (AGATE) is currently being designed. This will be a larger "2m-class" instrument with increased sensitivity and angular resolution. Large area, 2m x 2m drift changers are being developed for the imaging detector for this instrument. In addition to the large area imaging detector, large area anti-coincidence, coincidence and energy measuring systems will be required to complete the design of this instrument.

Summer research opportunities and Ph.D. thesis possibilities exist for students interested in these areas.



## 2.4 Theoretical Astrophysics

Theoretical studies are essential in order to determine the most important directions to pursue in future measurements, the interpretation of existing observations within a self-consistent framework, and in the development of new experimental techniques. Theoretical research is pursued in X-, gamma- and cosmic ray astrophysics, as well as in extragalactic astronomy, cosmology, compact object astrophysics, and solar physics.

The theory group presently supports three graduate students doing thesis research at Goddard Space Flight Center:

Yuan-Kuen Ko, working with Tim Kallman, is expected to complete her thesis work this year. She has been studying the effects of X-ray irradiation on the structure and dynamics of accretion disks in galactic X-ray binary sources.

Ramin Sina is working with Alice Harding on a thesis project involving the investigation of the triplet pair production process in strong magnetic fields. This past year, Sina completed an analytic calculation of the triplet pair production cross section, a third-order process, and has begun to evaluate the cross section numerically for a range of parameters. Preliminary results were presented in April at the APS Spring Meeting in Washington.

Jason Taylor is continuing his graduate work with Demos Kazanas on modeling the optical and UV line emission from active galaxies under the assumption that these lines are due to reprocessing of non-thermal radiation by red giant stars in a cluster near the active nucleus. Taylor has calculated the line profiles and the 1D and 2D line transfer functions for this system.

## 3. Future Efforts

Many of the projects described previously are ongoing and work will continue in the investigation of the relevant phenomena. Some more specific details are given below.

### 3.1.1 Cosmic Ray Detections

Some of the most significant questions in the field of particle astrophysics can be addressed by measurements of the isotopic composition of the cosmic radiation. The radioactive clock isotope  $^{10}\text{Be}$ , with a half-life of  $1.5 \times 10^6$  years, is a particularly important case. Measurements of the abundance of this isotope to relativistic energies, where time dilation effects become appreciable, will probe the density distribution of interstellar matter in the volume in which cosmic rays propagate. The Isotope Magnet Experiment (ISOMAX) is being