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ASTROPHYSICAL RESEARCH AT LAWRENCE LIVERMORE LABORATORY
PROPOSAL FOR A FORMAL PROGRAM

W. A. Lokke
C. B. Tarter

December 1979

Lawrence
Livermore
Laboratory

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I. INTRODUCTION

From the beginning, the Laboratory has had a significant history of accomplishments in astrophysics. The first calculations of supernova explosions, multi-dimensional simulations of star formation, and dynamic nucleosynthesis models all represent major theoretical and computational achievements. The field of soft x-ray astronomy was pioneered here, and our Laboratory has made critical nuclear physics and equation-of-state measurements. In turn, over the years, such research has strengthened the Laboratory's leadership in computational physics and enhanced the development of programmatically relevant experimental tools.

Today, however, only the theoretical astrophysics work remains active. The success and benefits of LLL's astrophysical activities, compared with the modest cost, suggest that broadening of its scope is well worth considering. In particular, we believe that revitalized experimental and observational efforts, established as an integrated part of astrophysics research would provide analogous benefits to such directly related Laboratory programs as x-ray diagnostics, radiochemistry, and experimental nuclear physics, while stimulating current theoretical work.

To encourage and guide our efforts in these areas, we propose forming an Astrophysical Research Program. Such a program could help coordinate current research activities, provide for peer review of new proposals, and act as a focal point for interactions with outside agencies and the scientific community. It would provide a natural mechanism for assessing the feasibility and impact of participating in large-scale observational or experimental projects. Since the benefits of such astrophysical research to LLL are directly tied to its intimate relationship to existing programmatic efforts, such a program would primarily operate through the existing management and organization

structure without the relocation of involved personnel. It would principally serve to enhance communication between part-time astrophysical workers, while ensuring that the quality of newly undertaken astrophysical projects meets the currently very high LLL standards of excellence and programmatic benefits.

We elaborate on these points in the following pages.

II. HISTORY AND STATUS

The incentive to develop an astrophysics capability dates from the earliest days of the Laboratory. In 1960, our computers, computational modeling experience, and the personal interests of the staff had led naturally to work in stellar structure and galaxy formation. Although the effort was small, the pioneering computational work of Colgate and White, May and White, Wilson and LeBlanc, and others in the 1960's provided the astrophysics community with spectacular examples of how powerful a tool computers can be in giving new insight into dynamical stellar processes.

A new component of astrophysics research emerged in the late 60's when a highly productive x-ray astronomy team grew out of staff interest in applying a programmatically developed technology to basic research. Supported with funds from the Readiness Program, the High Altitude Physics Group maintained a diagnostic capability for atmospheric testing. It also became one of the world's leading groups measuring low energy x-ray spectra from galactic sources. Since this work required considerable funding, it was terminated when the Readiness Program was phased out several years ago. More recently, experimental work in E Division aimed at developing better cosmological time scales was carried out under the sponsorship of the Physics Department.

What exists at the Laboratory today are scattered theoretical and computational centers of activity, little experimental work, and no observational

program. The theoretical effort ranges from numerical studies of black hole physics to atomic processes in the interstellar medium, and involves a number of part-time participants from the academic community. Nuclear Chemistry has proposed experiments complementary to those carried out in E Division, and former members of the x-ray group continue at a low level to pursue the possibility of outside funding for observational astronomy. There are meetings and seminars for interested staff members on roughly a bi-weekly basis. Overall, however, there is no attempt at coordinating the astrophysical research activities.

Despite the informal and fragmentary character of the work, the Laboratory has given astrophysics a state-of-the-art understanding of supernovae, the most advanced model for elemental abundances, and an experimental determination of the age of the universe.

III. PROGRAM RATIONALE

We suggest that a more structured program would enhance our theoretical work, and provide for a realistic expansion of the experimental and observational efforts. In turn, the Laboratory's weapons and related programs would receive increased benefits at a time when a CTB threatens their scientific capability.

Astrophysical research currently occupies a synergistic relationship with directly related weapons and physics research and represents roughly 5 FTEs spread over more than 20 scientists at LLL (see Appendix A). Computational astrophysics research has always been highly valued for its direct contributions to staff recruiting, morale, and creativity as well as its enhancement of LLL's scientific reputation. It also serves as a conduit for the introduction at LLL

of new ideas and techniques originated in the academic community. These benefits result from the fact that the same physics and computational techniques that are involved in weapon development (e.g., energy transport, material properties at high temperatures and densities, nuclear burn, and hydrodynamics) can be directly applied to some of the most exciting phenomena in modern astrophysics (e.g., supernovae, x-ray sources, nucleosynthesis, pulsars, black holes, etc.). In turn, the academic community addressing such phenomena provides a natural source of trained personnel, ideas, critical evaluation, and mutual stimulation of considerable importance to the weapons development community. Thus the Laboratory has been able to make important contributions to astrophysics while benefiting its own programs in a cost-effective manner.

The imminence of the CTB increases the importance of these benefits. Since the assurance of the nuclear weapon stockpile rests on staff vitality, a drastically reduced or nonexistent test program challenges our ability as a Laboratory to maintain weapons capability. By adding an expanded, coupled experimental program to an enhanced theoretical effort more staff members would find both stimulus and synergistic benefits in combining nuclear explosive work with part-time astrophysics. This stimulation would provide many with motivation to continue their involvement with weapons work and keep their minds and skills alive. It would also help attract high quality new staff members.

In addition to the sophisticated computational models of complex and programmatically relevant physical processes, the broad area of astrophysics provides a variety of experimental opportunities. Specific examples of mutually beneficial experimental projects include high sensitivity meteorite

isotope ratio measurements, x-ray mirrors and detector development, and measurement of nuclear cross-sections critical to nucleosynthesis. These projects would initially use existing experimental set-ups and equipment (e.g., Radiochemistry's mass spectrometers, ME's diamond-turning lathe, L-Division's x-ray diagnostics, and E Division's accelerators) to produce (relatively cheaply) long-sought-after astrophysical results, and at the same time provide the astrophysical community with a powerful incentive to improve these experimental techniques and equipment for both basic and programmatic use. In several cases, direct reimbursable support (e.g., from NASA, DOE/BES, etc.) for such joint development activities seems quite feasible.

Finally, as with any applied project a basic research program must pass tests of opportunity, importance, and excellence before it merits Laboratory recognition. Astrophysics qualifies in all respects. First, it is a dynamic and growing discipline, as every new observational technique continues to reveal. The sky is filled with dramatic, unexplained events, taxing our powers of modeling and understanding. Second, there is strong national interest in astrophysics as evidenced by NASA's budget and by the popularization of black holes, quasars, and other phenomena which excite the public's imagination. Finally, LLL already has experts in both experimental and computational areas; expanded research would attract more.

Management's recognition of a formal research program would aid the currently active theoretical efforts by encouraging closer contact among LLL astrophysics researchers, and from the stimulus that experimental work always brings to theorists. The experimentalists would derive direct benefits by having a well-defined sponsor for their external proposals, and by providing a mechanism for carrying out projects that necessarily involve support staff. More generally the entire staff would recognize management support of astrophysics as a manifest commitment of the Laboratory to basic research--and would share in the excitement

publicized triumphs would bring.

IV. PROGRAM DEFINITION

We propose a simple management structure since the size and scope of the initial program are small. A rotating post as Astrophysics Research Coordinator would be established as the management contact for the program. Since much of the existing astrophysical research is in the Physics Department, we suggest that the Research Coordinator report to the Associate Director for Physics. The administration of the program would then be carried out by the Astrophysics Research Coordinator and the Program Manager for Physics.

Because of its close relationship with programmatic efforts, the program would primarily operate through the existing organizational structure without the relocation of personnel. Any expansion of the program, particularly the establishment of an active observational group, would be reviewed by management in the context of LLL Astrophysics and other Laboratory long term goals. Since outside funding from NASA might compete with weapon programs for available skills the Associate Directors for Nuclear Testing and Nuclear Explosives Programs might want to be given approval authority or be more directly involved in proposals to external agencies.

The Astrophysics Research Coordinator would plan to initiate management and technical reviews of new research areas. He would address the problem of getting the best out of part-time workers--the majority of the program contributors, and would encourage participation by post-docs, sabbatical visitors, and consultants. He would also be responsible for reporting to management and outside groups on research progress.

Because of the diverse nature and divisional affiliations of the staff working in astrophysics, the Astrophysics Research Coordinator will form and

chair a steering committee to oversee, review and evaluate the major areas of research. The steering committee's primary function would be to provide peer review for the external research proposals and act as a clearing house for information dissemination. It would also be responsible for ensuring the quality of all work carried out under the auspices of the Astrophysics Research Program.

The major categories of future astrophysical research will closely resemble past efforts. Theoretical work will continue at roughly its present level, with some modest expansion in selected areas. We hope to reactivate the x-ray observational capability and to initiate experimental projects in the nuclear physics and equation-of-state areas that will complement theoretical analysis. A sketch of the relationships among these program components is shown in Figure 1. A more detailed description of possible future projects is given below.

A) Theoretical Effort

The current Laboratory level of effort for theoretical astrophysics research includes over 20 participants (almost all part-time) from nine scientific divisions at the Laboratory with students, consultants, and guests occasionally participating. A partial listing of the LLL researchers is given in Appendix A. We anticipate no major expansion of this effort, although significant gains might be achieved by modest additions of support personnel. The stimulus of experimental work would encourage even more interaction with guests and consultants and call for additional contributions from staff members with interests in special topics.

As in the past the theoretical work will be strongly focused in areas that need the Laboratory's large scale computational facilities: modeling explosive stellar phenomena, dynamical processes in the interstellar medium, nucleosynthesis,

Astrophysics Research Program

Figure 1 - A complete astrophysics program needs an active relationship between theory and experiment.

and material properties. Further in the future it may be worth exploring the possibility of becoming a national computational center for astrophysics. As in the case of the MFE center, the on-site development and use of independently derived software would benefit our computationally intensive Laboratory.

B) Experimental Work

Activities in experimental physics will emphasize measurements that are similar (and in many cases, identical) to those that are carried out for programmatic purposes. These include determination of the thermodynamic properties of matter at high temperature and density, opacity and detailed spectroscopic measurements, and experiments on plasma heating and confinement. In all such cases, the basic laboratory technique is the production (through deposition of laser energy, for example) and accurate diagnosis of a hot dense plasma.

A second general area of interest is in nuclear physics and radiochemistry. Measurements of key nuclear cross sections can be extremely important to the development of accurate nucleosynthesis models. Conversely, measurements of galactic and terrestrial elemental abundances can lead to new insights into nuclear processes. The focus in nuclear physics and radiochemistry will be on the use of existing equipment and diagnostic techniques for abundance determinations of radioactive nuclei and for measurements of selected nuclear cross sections.

C) Observational Proposals

We feel the x-ray observational effort should be reactivated to advance the Laboratory's x-ray diagnostic capability and provide a stimulus for theoretical work. The Laboratory derived numerous benefits from the observational astrophysics effort in the past including the development of x-ray microscopes and non-focusing imaging techniques with coded apertures. The

are now used routinely to obtain x-ray images of hot laboratory plasmas. Also, since the projects were systems-oriented, requiring broad support from electronics, vibrational analysis, optical analysis and materials technology, they exercised the Laboratory's matrix mode of operation and promoted team effort. The proposed observational x-ray effort will provide similar benefits to the Laboratory in the future.

The funds to support the observational activities will primarily be sought from NASA, although some of the research overlapping the verification area could possibly be funded by ARPA, AFTAC, or ISA/DOE. LLL has an excellent reputation for high-altitude observations with over seventy technical publications on the work done between 1965 and 1976. This strong past record should greatly facilitate obtaining support for future research.

We envisage a three-phase program, beginning with participation as guest observers and proceeding to integral team status on space lab missions. Our initial steps will be to obtain observational data for interpretation and publication through NASA's Guest Observer Program for the Einstein Satellite Observatory. Simultaneously, we plan to submit proposals for rocket payloads; if successful, these will form the basis for our ultimate participation in space lab.

An integral aspect of such activities is the development and fabrication of the associated instrumentation. This will also benefit both programmatic efforts and other x-ray astronomy groups, and can thus proceed somewhat independently of the specific x-ray proposals. In particular, the construction of an axisymmetric diamond-turned metallic mirror of the required size and tolerances will require state-of-the-art advances. Support for this work will be used to structurally modify LLL's DIM-2 facility, providing an enhanced capability

for the Laboratory. Similarly, the development of position sensitive proportional counters will have immediate application as an addition to our x-ray calibration facility.

V. SUMMARY

Basic research is often characterized as self-directed, moving on its own timescale, spurred by the unexpected. An effective, organized basic astrophysics research program does not have to be a contradiction in terms. A broadly chartered, long-range LLL Astrophysics Research Program, created and recognized by LLL management, can benefit the general scientific community, stimulate the staff, maintain important capability, and enrich the Laboratory.

APPENDIX A

Staff Members with Astrophysical Research Interests

<u>Division</u>	<u>Name</u>	<u>Research Interests</u>
T	Alder, Berni	Related EOS studies, particularly phase equilibria
T	Axelrod, Tim	γ -ray astrophysics, supernovae
E	Berman, Barry	Photon and neutron-induced nuclear reactions
B	Bowers, Dick	Neutron star EOS, neutrino transport
L	Burginyon, Gary	Observational x-ray astronomy
T	Chapline, George	Properties of dense matter, x- and γ -ray sources
H	DeWitt, Hugh	Related EOS studies
G	Duewer, Bill	Planetary atmospheres
T	Eltgroth, Pete	Relativity and relativistic hydrodynamics
A	Eppley, Ken	Black holes and gravitational radiation
A	Grasberger, Bill	Stellar atmospheres and radiative transfer
H	Graboske, Hal	Early stellar evolution
B	Hainebach, Kem	Stellar evolution and element abundances
T	Howard, Mike	Nucleosynthesis
B	LeBlanc, Jim	Physics of collapsing objects
A	Max, Claire	Plasma astrophysics, pulsars
H	More, Dick	EOS properties
B	Norman, Mike	Star formation
A	Orth, Charles	Cosmic ray physics
T	Penner, Joyce	Planetary atmospheres
Y	Swift, Charlie	X-ray and infrared observations
L	Stoering, Pete	X-ray astronomy
T	Tarter, Bruce	Quasars and x-ray sources

<u>Division</u>	<u>Name</u>	<u>Research/Interests</u>
Do.	Teller, Edward	High energy astrophysics
L	Toor, Art	X-ray observations
Q	Wainwright, Tom	Physical processes
O	Weaver, Tom	Supernovae and nucleosynthesis
L	West, Harry	Space physics
T	White, Dick	Hydrodynamic collapse, relativity
B	Wilson, Jim	Relativistic hydrodynamics, supernovae, x-ray sources
O	Wood, Lowell	Supernovae
T	Woodward, Paul	Star and galaxy formation
A	Zimmerman, George	Interstellar medium, stellar evolution

APPENDIX B

A brief summary of recent astrophysical research can be obtained from the Observatory Reports published for the last several years in the Bulletin of The American Astronomical Society. A copy of this year's edition is given below; previous reports were published in Bull. Am. Astr. Soc. 7, 316 (1975); 8, 172 (1976); 9, 137 (1977); 10, 204 (1978).

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I. INTRODUCTION

The Lawrence Livermore Laboratory (LLL) is operated by the University of California under Department of Energy contract W-7405-ENG-48. Most of the astrophysical and astronomical research at LLL represents part-time activity associated with the main responsibilities of staff members. Among those whose activities include such research, visitors this past summer included D. Eardley (Yale U.), L. Smart (Center for Astrophysics), R. Talbot (Rice U.), and S. Woosley (Univ. California, Santa Cruz). Recently, K. Eppley and P. Woodward joined the professional staff.

Research related to astronomy at LLL can be roughly divided among three categories: theoretical and computational astrophysics, high-altitude observations, and theoretical and experimental determination of atomic and nuclear properties. Facilities utilized in this work include four CDC 7600 and two CDC STAR-100 computers, sounding rockets (developed by Sandia Laboratories) launched from Kauai, several accelerators, including a cyclotron and a 100-MeV electron-positron LINAC, and an array of equipment for carrying out experiments on the properties of materials at high pressures and densities.

II. STELLAR EVOLUTION AND NUCLEOSYNTHESIS

Weaver, in collaboration with Woosley (Univ. California, Santa Cruz) and Zimmerman, has continued the development and application of the KEPLER stellar evolution/explosion code, which combines implicit hydrodynamics with a comprehensive treatment of nuclear reactions. Their model has been used to follow the evolution of 15 and 25 $M_{\odot}$ stars from the zero-age main sequence through iron core collapse and ensuing supernova explosion. The explosive phase was treated by linking the collapsing core of the presupernova models to Wilson's detailed supernova-core computer code, which followed the core's evolution through collapse, bounce, and outward-going shock wave formation. These results were then relinked back to the KEPLER code to calculate the explosive nucleosynthesis and observable light output that occurs as the shock waves sweep through and break out of the surface of the star.

These calculations, which are the first to explore in detail the entire (postbirth) life cycle of complete stars, give light curves and nucleosynthesis outputs that are in striking agreement with observations. In particular, the relative ratios of the elemental abundances over the range from oxygen to iron in the ejected debris of the 25 $M_{\odot}$ star are in good agreement with those seen in the solar system. Explosive processes are found to be primarily responsible for the production of elements between silicon and iron, while those from oxygen to magnesium are formed hydrostatically and are largely unmodified by their explosive ejection. The 15 $M_{\odot}$ star debris remains predominantly enhanced in neon, magnesium, and silicon, reflecting its presupernova composition. These results are in accordance with observed stellar birth rates, which suggest that stars in the mass range near 25 $M_{\odot}$ contribute the greatest total mass of heavy-element ejecta to the interstellar medium.

Another very important experimental check on these mod-

els is that the calculated temperature, velocity, and radius of the photosphere during the supernova explosion of the 15 $M_{\odot}$ star agree within the observational errors with Supernova 1969f, the best observed type II supernova, with no adjustment of parameters. Work is currently underway to extend those results to other mass stars, and to study the sensitivity of the results to uncertainties involving convection and supernova core physics.

Weaver and Woosley have also developed a nuclear-post-processor code (BURN) which follows the evolution of 131 isotopes from hydrogen through the iron peak based on the thermodynamic conditions found by KEPLER. Extensive postprocessing has been performed for 15, 20, and 25 $M_{\odot}$ models and has suggested origins for a number of the isotopic anomalies recently observed in meteorites, as well as possible sites for the r , s , and p processes. It is hoped that the combined results of KEPLER and BURN will provide a self-consistent, and, as far as possible, parameter-free synthesis between stellar evolution and the various nuclear processes believed responsible for the production of the chemical elements.

Wilson has carried out one-dimensional stellar core collapse and supernova calculations utilizing new equations of state and electron capture rates. The use of new values of the statistical weight for heavy nuclei at high temperatures has softened the equation of state considerably, and the electron capture rates on heavy nuclei have been increased. Compared with previous calculations, the principle effect of these changes is to increase the density at which bounce occurs ($2 \times 10^{10} \leq \rho \leq 6 \times 10^{10} \text{ g/cm}^3$), and to increase the infall kinetic energy before bounce. The strength of the outgoing shock is now sensitive to the strength of the neutrino elastic scattering because of the higher infall velocity and hence higher temperatures. For conventional cross sections the shock is so weakened by neutrino emission that the outer layers of the core do not attain escape velocities. An increase in elastic scattering by a factor of 10 or more is needed to produce an explosion due to core collapse.

Norman and Wilson are also investigating the stability of stellar core bounces. The objective of this study is to determine whether large amounts of gravitational radiation could be emitted from only slightly nonspherical collapse. Such behavior has been predicted on the basis of ellipsoidal model calculations, and the difficult two-dimensional calculations needed to test this hypothesis are underway.

III. NEBULAE AND THE INTERSTELLAR MEDIUM

Butler (Harvard), Dalgarno (Harvard), Weisheit, and Bender studied the charge transfer reaction $O^+ + H \rightarrow O + H^+$. Preliminary analysis of the potential surfaces indicates a larger thermal rate coefficient for this reaction, $\sim 10^{-10} \text{ cm}^3/\text{s}$, than previously believed because of important interactions involving doubly excited electronic states of the OH^+ molecule. Such a large rate coefficient could explain numerous anomalies in nebular emission-line spectra.

Weisheit, Tarter, and Oppenheimer (Center for Astrophysics) have investigated the effects that a large, diffuse flux of low-energy cosmic rays would have on the ultraviolet absorp-

tion-line spectra of evolving HII regions surrounding OB stars. Observations made with a large space telescope may be able to place significant upper limits on the ionization rate produced by such a flux.

Woodward has continued to develop his hydrodynamic code, MUSCL, and apply it to gas dynamical problems in the interstellar medium. A version of the code designed to simulate disk galaxies has been used to compute the response of a gaseous disk to an external spiral gravitational potential. This work shows the development of shocks in two dimensions with no limiting assumption that the spiral arms which form must be tightly wound. Self-gravity of the gas is now being incorporated, and this will make it possible to study the development of global modes of instability of the gaseous disks. This version of MUSCL will also be used to analyze the gravitational collapse of rotating gas clouds.

The MUSCL code is also being utilized to study the interaction of newly formed stars with the dense clouds around them. This requires the development of a multifluid version of the code to follow ionization fronts and the shocks immediately preceding them on a two-dimensional Eulerian grid. The objective of this study is to estimate the efficiency of star formation chain reactions relative to other processes in a variety of likely environments.

Norman has been investigating the collapse of rotating interstellar gas clouds using a new, higher-order, accurate, two-dimensional hydrodynamics code. Using a variety of grid resolutions, he has shown that the rings found by other workers are zoning dependent, and that with sufficiently fine zoning near the rotation axis, the collapse leads to a flattened disklike configuration rather than a ring. Although these results are preliminary, the numerical difficulties of such highly convergent flows are beginning to be elucidated.

IV. HIGH-ENERGY ASTROPHYSICS

Krolik (Instit. Advanced Study), McKee (Univ. California), and Tarter have continued their study of heating and cooling processes in quasars and active galactic nuclei. Specifically, they have analyzed the heating produced by the radio, infrared, and hard x-ray portions of the spectrum (in addition to the conventional ultraviolet radiation), and have also considered the effects of other external sources such as cosmic rays. These additional energy sources can significantly influence the thermal properties of the line emitting regions and can lead to objects that display a variety of emission line spectra ranging from "typical nebular," to very high excitation, to cases in which the visible and ultraviolet are essentially featureless. The imposition of pressure equilibrium also yields a number of constraints on the background medium in which the emission-line clouds are imbedded. Axelrod is currently calculating the detailed gamma-ray emission expected from type II supernova. The hydrodynamic variables and isotopic abundances required to perform the gamma-ray transport in the expanding supernova are derived from KEPLER calculations. (See Sec. II.) The gamma-ray transport is done in the discrete ordinate formulation of the transport equation, which is suitable for the wide range of optical depths encountered in such problems.

Preliminary results indicate that gamma ray lines, predominantly from the decay of Ni^{64} , first begin to appear above the Compton scattered continuum about 100 days after explosion, and rapidly increase in intensity, reaching a maximum about 500 days after the explosion of $15\text{--}25 M_{\odot}$ stars. At later times,

lines from longer-lived isotopes, such as AP^{24} and Ti^{44} , begin to dominate the spectrum. The predicted intensities are such that a type II supernova from the galactic center, or possibly the Magellanic clouds, should be clearly observable by the upcoming gamma-ray experiments (HEAO-C, GRO) (given the rather unlikely assumption that such an event occurs during the observation time). Detection of gamma rays from an extragalactic supernova seems unlikely with present instrumental characteristics.

Eppley and Smarr (Center for Astrophysics) have continued their calculations of gravitational radiation from the collisions of two black holes. At present, study has been made of head-on, irrotational collisions with no matter present, resulting in a maximum energy release in gravitational waves of approximately 0.001 of the rest energy. The frequency spectrum and angular distribution strongly resemble that of a point particle falling into a Schwarzschild black hole. In related work, Eppley has evolved pure gravitational waves to study the calculation of mass-loss in numerically generated spacetimes. It was found that mass-loss expressions constructed from the curvatures were more accurate than formulas built from the Christoffel symbols in spacetimes with very strong-field regions, i.e., black holes.

Wilson has continued to use his axially symmetric relativistic hydrodynamic computer code to calculate the gravitational radiation emitted by collapsing stars. Well-distorted neutron star bounces that occur at nearly peak allowable density emitted 1%–2% of their rest energy as gravitational radiation. The head on collision of neutron stars falling from infinity has also been calculated. Again, about 1% of the rest energy is emitted as gravitational radiation in the most extreme case. Work is also continuing on the code to enable it to calculate the more difficult problem of gravitational radiation emission during black hole formation.

V. RELATED RESEARCH

From a calculation based on the dilute Debye-Hückel theory with Abc concentration corrections, Alder and Pringle predicted that ions such as FeXXV would phase separate from a hydrogen plasma. They estimated a critical temperature of about 10^7 K and a critical concentration of approximately 10 parts FeXXV for a pressure appropriate to the solar interior.

Because of the rather unsatisfactory convergence of the concentration expansion, the model was numerically investigated by molecular dynamics calculations which could also be compared to the predictions of the approximate hypernetted chain integral equation. The comparison was carried out satisfactorily, and the more accurate theory yielded roughly the same critical concentration but a critical temperature of about $5 \times 10^6 \text{ K}$. This temperature is somewhat too low to lead to phase separation of FeXXV under conditions in the solar interior, but the model is still too crude to eliminate that possibility. Work on an improved theoretical model involving nonuniform electron distributions is being pursued.

Wilson, Bowers, and Tubbs (Caltech) are comparing Monte Carlo and Fokker-Planck representations of neutrino thermalization under conditions during stellar core collapse, where the thermalization rate is important ($\rho \approx 10^9 \text{ g/cm}^3$ and $T \approx 10^9 \text{ K}$). The principle scattering mechanism is assumed to be electron-nucleon elastic scattering. Neutrino and electron degeneracy effects are included in the Fokker-Planck algorithms. Neutrino energy and number densities and loss rates are being examined. Preliminary numerical results indicate

that the Fokker-Planck method can be normalized to reproduce the Monte Carlo results.

Weisheit examined the importance of nonlinear ion Stark broadening of lines from He-like ions in very dense plasmas. At densities comparable to solid materials, the quasistatic ion broadening is as significant as impact broadening by electrons.

Penner and Chang calculated changes in ozone, temperature, and other minor constituents resulting from 11-yr variations in the solar flux between 1800 and 2400 Å. Results were computed using a one-dimensional time-dependent model that allows for all major feedbacks and time delays which may result from changing photolysis rates in the O_3 , NO , HO , ClO , system.

The ozone response to a variety of solar conditions was shown to depend on the relative ratio of ultraviolet variability above and below about 2550 Å. They found that the temperature increase due to increased heating by ozone absorption significantly affects the total ozone variation above 30 km. Ozone changes associated with solar flux variations are pri-

marily due to changes in the photolysis rates of O_3 and O , and only secondarily due to changes in other minor species.

Since the 1950's the chlorine content of the stratosphere has been increasing. The effect of this increase on ozone variability during the last two solar cycles was analyzed. It was concluded that the ozone record is apparently consistent with solar flux variations of the magnitude used, although more data are required to fully establish this relationship. In particular, the magnitude of the ozone decrease caused by increased use of fluorocarbons appears to be within the uncertainties that could be attributed to changes in the solar ultraviolet flux.

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C. BRUCE TARTER