The Joint Institute for Laboratory Astrophysics functions as a cooperative scientific venture of the National Bureau of Standards and the University of Colorado. Housed on the University of Colorado campus, JILA draws its scientific staff from the two parent organizations. Research is conducted at JILA in a number of areas of atomic physics and astrophysics: stellar atmospheres and radiative transfer; stellar interiors; solar physics; the interstellar medium and galactic astronomy; atomic collisions, both theoretical and experimental; spectroscopy and line broadening; chemical physics; optical resonance phenomena; and precision measurements.

I. PERSONNEL

Recent additions to the permanent scientific staff of JILA have been Dr. Richard McCray, formerly of Harvard University; Dr. Juri Toomre, formerly of New York University; Dr. Peter Conti, formerly of Lick Observatory; and Dr. James Fallier, formerly of Wesleyan University, Middletown, Connecticut.

There were 11 visiting fellows resident in JILA during 1971 - 1972. They are: Dr. Peter Conti, Lick Observatory, Santa Cruz, California; Dr. Vernon Ehlers, Calvin College, Grand Rapids, Michigan; Dr. Robert Futrelle, North American Rockwell Co., Santa Monica, California; Dr. Icko Iben, Massachusetts Institute of Technology, Cambridge, Massachusetts; Dr. Janet Lesh, Observatoire de Paris, Meudon, France; Dr. Bruce Mahan, University of California, Berkeley, California; Dr. David Moore, University College, London, England; Dr. James Peek, Sandia Corporation, Albuquerque, New Mexico; Dr. Ian Percival, University of Stirling, Stirling, Scotland; Dr. William Reinhardt, Harvard University, Cambridge, Massachusetts; and Mr. Theodore Stecher, Goddard Space Flight Center, Greenbelt, Maryland.

Those who were Postdoctoral Research Associates during the year are: Dr. Basim Bulos, Columbia University; Dr. Joseph Cassinelli, University of Washington; Dr. David Candler, University of Missouri at Rolla; Dr. J. Scott Hildum, University of Colorado; Dr. Hartmut Hotop, University of Freiburg; Dr. John Jenkins, Imperial College, London; Dr. Roy Lang, Massachusetts Institute of Technology; Dr. Dietmar Lauterborn, Hamburger Sternwarte; Dr. John Leibacher, Harvard University; Dr. Michael McCusker, Rice University; Dr. David Norcross, University College, London; Dr. Halla Odabasi, University of Colorado; and Dr. Fred Walls, University of Washington. In addition, Dr. Rafael Steinitz, Tel-Aviv University, spent the year at JILA as a visiting scientist.

Thirty-one graduate students pursued their research in JILA in 1971 - 1972 and three of these completed their Ph. D. degrees: Russell Bennett, Nelson Jalufka, and Paul Taylor.

Three fellowships were available at other institutions during the year 1971 - 1972. J. P. Cox was a Visiting Professor at Monash University, Melbourne, Australia, during the spring 1972. A. C. Gallagher visited the University of Otago, Dunedin, New Zealand, during spring 1972. R. H. Garstang spent fall 1971, at the University of California at Santa Cruz. He was also President of the 1972 Liege International Astrophysical Symposium on Planetary Nebulae.

II. CONFERENCES

Three conferences held in Boulder during the year involved JILA staff members. The Third International Conference on Atomic Physics was held 7 - 11 August 1972, for which Dr. Stephen J. Smith was the Organizing Chairman. The Conference on Radiationless Transitions in Gaseous Molecules occurred 16 - 18 August 1972, and was organized by Dr. Richard Zare of Columbia University and Dr. W. Carl Lineberger of JILA. A. U. Symposium 53, the Conference on Physics of Dense Matter, was held 21 - 26 August 1972, with Drs. Wesley Brittin and Carl Hansen of JILA as the local organizing committee.

III. RESEARCH ACTIVITY IN 1971 - 1972

The work which is described in this section is that portion of the total JILA effort in astrophysics and atomic physics which is of direct interest to astronomers. Other aspects of JILA research in atomic physics which do not have immediate consequences for astronomical problems, but which strengthen the overall program, are not described here, but their scope is evident from the publicatioin list in Sec. IV.

General Topics: J. P. Hauser and P. L. Bender conducted preliminary analyses of laser range measurements to optical retroreflectors placed on the lunar surface by the Apollo missions. This work is being done in cooperation with the University of Texas, the Jet Propulsion Laboratory, and other institutions, using data obtained by the McDonald Observatory. Also, further work has been carried out on an analytic error analysis model for the lunar range problem.
R. L. Barger and J. L. Hall completed a highly accurate measurement of the wavelength of the methane-stabilized laser in terms of the internationally accepted length standard, which is based on the orange line of krypton. The final uncertainty of 3.5 parts in $10^8$ was caused mainly by the properties of the krypton standard. At the same time, a measurement of the methane-stabilized laser frequency accurate to 6 parts in $10^{11}$ was obtained by Evenson, Wells, Peterson, Danielson, and Day of the NBS Quantum Electronics Division. The wavelength and frequency results were combined to give a new value for the speed of light accurate to 3.6 parts in $10^9$.

J. Levine and R. Stebbins carried out a search for gravitational radiation from the pulsar in the Crab nebula using a unique type of laser interferometer. A 3.39-μm laser was locked to a 30-m vacuum Fabry–Perot interferometer with its mirrors mounted on pivots in an unused gold mine near Boulder. The locked laser was beat against a methane-stabilized laser to detect earth motion at one or two times the pulsar frequency. The limit set on the earth strain at these frequencies was 8 parts in $10^{17}$.


J. P. Cox has prepared for publication an extensive review on pulsating stars.


Radiative Transfer and Stellar Atmospheres: D. G. Hummer and P. B. Kunasz investigated the formation of spectral lines in extended spherical atmospheres using a generalization of the variable geometry factor procedure, and have prepared for publication a very fast, compact and efficient computer program to perform the formal solution of any static spherical transfer problem. They have also solved the transfer problem in a spectral doublet for an externally illuminated gas. This work has application to the interpretation of laboratory experiments by A. V. Phelps.

J. I. Castor has completed a study of radiation transport in a spherically symmetric moving medium in an attempt to clarify the situation regarding effects on the transport attributable to the finite speed of light. This work should have application to stellar pulsation and to stellar winds; in fact, there is an indication that some treatments of stellar winds are in error owing to the neglect of these effects.

R. Steinitz is studying the frequency dependence of the source function as manifested in the differences between the absorption and emission coefficients.

R. N. Thomas, in collaboration with J.-C. Pecker and F. Praderie (Institut d’Astrophysique, Paris), continues to explore the physical significance of a stellar atmosphere as a transition between the stellar interior and the interstellar medium.

K. B. Gebbie, R. Steinitz, and J. Cassinelli (Washington Observatory) have examined the relation between the gray and nongray temperature distributions in extended model atmospheres.

D. D. Hummer and D. M. Mihalas (High Altitude Observatory) have examined the excitation mechanism of the NIII emission line $\lambda 4634, 4640$ seen in the spectra of Of stars, and have found quantitative agreement between the equivalent widths predicted using non-LTE plane-parallel model atmospheres and Conti’s recent measurements of equivalent widths in stars classified O((f)) in Walborn’s system.

J. I. Castor and J. J. Castor have studied a simplified stellar wind model in order to shed additional light on the role radiative processes play in determining the structure of the wind. This model assumes that the outflowing gas is optically transparent to the radiation emanating from a central point source. It is found that radiative heating is indispensable for the flow, and that the effect of radiation pressure is to set the scale of the flow, so that with increasing radiation pressure, the wind assumes a more important place in the overall structure.

J. L. Linsky, T. R. Ayres, and R. A. Shine have obtained high-resolution absolute flux profiles for the CaII K and 8542 lines in Procyon (F5 V-V) using the Kitt Peak solar telescope. These data have led to a one-component hydrostatic equilibrium model for the chromosphere of Procyon, which can be obtained from models of the quiet sun by simple scaling laws. It appears that the temperature minima for stars of type F through middle G are proportional to the effective temperatures.

F. Praderie, J. L. Linsky, T. R. Ayres, and R. A. Shine have observed the CaII H and K lines in the A stars Sirius, Vega, and Deneb. The H line in Vega appears to show a central emission feature indicating the existence of a chromosphere.

R. H. Garstang and S. B. Kemen continued their work on the spectrum of helium in a large magnetic field, such as that of a white dwarf with a dipole magnetic field; predictions were made of the line profiles as a function of the field strength, and the orientation of the assumed dipole field relative to the line of sight. The prediction is that spectral lines should still be observable and not broadened out of visibility, up to at least $10^7$ G.

Solar Physics: R. N. Thomas has suggested an interpretation of the correlations between intensity fluctuations in the continuum and those in the lines CaII $H$ and $K$, Mg b, and Hα, as measured by J. W. Evans and C. P. Catalano of Sacramento Peak Observatory. K. B. Gebbie and R. Steinitz are exploring mechanisms for the production of light and dark contrasts in the observed intensity of radiatively controlled spectral lines.

K. B. Gebbie and R. N. Thomas, in collaboration with E. H. Avrett (Smithsonian Astrophysical Observatory), are reviewing solar chromospheric models in order to assess the extent to which each represents a true picture of the sun in terms of the observed data and the physical processes taking place in its atmosphere.

R. Steinitz, in collaboration with M. Altschuler (High Altitude Observatory), is studying the geometrical time evolution of the dipole and quadrupole components of the solar magnetic field.

R. A. Shine and J. L. Linsky have computed a grid of solar chromospheric plage models based upon their photoelectric profiles of five CaII resonance and subordin ate lines in plages of different brightness. They conclude that bright plage temperatures are still lower, the pressures are much higher, and the middle chromosphere occurs much lower, than in quiet regions. They are presently working on models for the chromosphere.
above a sunspot, and studying the influence of acoustic waves on line profiles. J. L. Linsky has evaluated the accuracy with which the moon may be considered an absolute radiometric standard for infrared and microwave observations of extended sources. Based upon this work, he has recalibrated the solar spectrum from 1 mm to 20 mm, considerably reducing the previous scatter. He finds that there appears to be a broad absorption feature near 8 mm.

D. B. Brown has obtained and reduced a series of simultaneous spectrograms taken in the C$\alpha$ H, K, L$\beta$542, and L$\alpha$498; Na D; and H$\alpha$ lines in active and quiet regions, using the solar tower telescope at Sacramento Peak Observatory. He is correlating the data, and will compute models for small-scale chromospheric structures.

G. H. Mount, R. A. Shine, and J. L. Linsky have obtained a center-to-limb series of photoelectric spectra and spectroheliograms in the L$\beta$883 bandhead of CN. They are presently analyzing the data to determine physical properties of small-scale network structures in the upper atmosphere.

J. W. Leibacher has continued work on the interpretation of the observed motions and nonradiative transfer of energy near the visible surface of the Sun. In particular, he is investigating the overstability of nonradial acoustic modes which would drive the five-minute oscillation of the photosphere and chromosphere. An observational program designed to elucidate the initiation and decay of the photospheric oscillations, has begun at the Kitt Peak National Observatory in collaboration with O. R. White of the High Altitude Observatory and J. W. Harvey of Kitt Peak.

P. Ullschneider and L. F. Oster have continued their studies of propagation and decay of mechanical energy modes in the outer atmospheres of the sun and stars. In the solar case, for which the dissipation of acoustic waves in the chromosphere agrees very well with the height variation of the radiative losses, attempts were made to reproduce the empirical microturbulent velocities by identifying them with the velocity fields in periodic waves. Preliminary results are very promising. A detailed calculation of the ensuing line profiles for crucial chromospheric lines, such as C$\alpha$ H and K, is underway.

L. F. Oster and J. T. Mariska have studied a variety of photospheric solar phenomena for possible correlation with nonradial and radial maxima of geomagnetic activity. They found that none of these phenomena, including the structure of the photospheric magnetic field, can be cited unambiguously as a source of geomagnetic disturbance. Instead, it was found that the large-scale structure of the coronal magnetic field appears to be the sole agent. A detailed study is underway in collaboration with M. Altshuler and D. E. Trotter of the High Altitude Observatory.

Stellar Interiors: A preliminary survey of the linearized pulsations of Cepheid variables has been completed by J. P. Cox with D. S. King of the University of New Mexico. Some of the models have also been investigated using nonlinear pulsation calculations. These results suggest that the mode, fundamental or first overtone, in which a star pulsates at large amplitude may depend on initial conditions over a relatively wide range of parameter values. One goal of this work is to strengthen the connection between the linear and nonlinear theories, perhaps even to be able to predict the mode behavior from the very fast linearized calculations.

J. I. Castor has continued to examine the pulsation properties of RR Lyrae stars. Linear instability calculations using the new stellar opacities computed by A. N. Cox, A. L. Merts, and N. Magre at Los Alamos have confirmed the earlier results that suggested upward variations in the effective temperatures and luminosities of cluster RR Lyrae stars. Castor has worked at Los Alamos on new, efficient computational methods for stellar pulsation, which eliminate the difficulties associated with the hydrogen ionization zone.

An extensive program of nonlinear dynamical calculations of RR Lyrae star models has been undertaken by W. Spangenberg at the facilities of Los Alamos Scientific Laboratory, in order to show the relation of linear to nonlinear models when the same gas properties are used for each, and especially to examine in detail the validity of the luminosity-transition period relation obtained by Christy.

R. Stellingwerf has studied the nonlinear, periodic behavior of a simplified one-zone model of a pulsating star, and obtained surprisingly realistic light curves. He is also investigating a new method of obtaining periodic solutions of the nonlinear pulsation equations. The new method should permit one to test the stability of the large-amplitude mode behavior, something which is both extremely costly and often ambiguous using the conventional dynamical method.

C. J. Hansen, with H. M. Van Horn, and M. B. Richardson of the University of Rochester, has completed a preliminary investigation of the radial pulsations of the white dwarf star. J. P. Cox has in the meantime studied the problem of the pulsational stability of stars in thermal imbalance. The latter work will be used in a joint effort by Cox, Hansen, and Van Horn to give a more refined treatment of the pulsational stability of cooling white dwarfs.

Following a study by Visiting Fellow J. Leah and M. Azizennan of the University of Montreal on the location of $\beta$ Cephei stars in the H-R diagram, Leah and Azizennan collaborated with J. P. Cox and with R. van der Borgh of Monash University in attempting to find the basic destabilizing mechanism, but without definite success. P. Stry is studying the dynamical stability of models of very luminous red supergiants in which curvature of the atmosphere is important, and also the nonlinear dynamical behavior of the envelopes of these stars. One goal of this work is to examine the problem of mass loss from their surfaces.

C. J. Hansen and J. P. Cox continued their investigations of the secular stability of helium stars. A new unstable mode, the existence of which had been suggested by Y. Osaki, has been found for models on the high-density branch of the double-valued, helium-burning main sequence. The secular stability of simplified models of stars on the lower hydrogen main sequence was investigated by R. Stellingwerf and J. P. Cox. They found that models on the high-density branch of this double-valued sequence would be secularly unstable if this branch existed. In connection with these studies of secular
stability, C. J. Hansen has exhibited the direct relation between the thermal diffusion and secular time scales in simple stellar envelopes.

F. W. Makaloff and C. J. Hansen, in collaboration with R. McCray and J. Toomre, have started an effort to investigate various topics relating to supernova explosions, galactic structure, and the interstellar medium using methods for treating hydrodynamics in two space dimensions.

C. Newcomb of the University of Denver, with J. P. Cox, is beginning to investigate the effects of slow rotation on stellar pulsation using a similar approach.

D. Lauterborn continued his work on trying to establish which physical factors determine the properties of "loops" in the Hertzsprung - Russell diagram during the central helium burning phase of stellar evolution. He extended this work, in collaboration with S. Refsdal and R. Stabell of the University of Oslo, to horizontal branch stars. He also obtained and discussed multiple solutions of the stellar structure equations during the "loop" phases. In collaboration with A. Weigert (Hamburger Sternwarte), he investigated the mass loss from the component of a close binary system having an extensive outer convective envelope.

E. B. Aronson and C. J. Hansen have investigated some of the thermodynamic properties of equilibrium gaseous masers when coupling with the gravitational field is taken into account. The discussion has a direct bearing on the method of performing the transition from statistical mechanics to thermodynamics with gravitation. The work of J. Toomre (with E. A. Spiegel at Columbia, and J. -P. Zahn at Nice) on compressible convection over multiple scale heights using an elastic modal representation is in considerable contrast to mixing-length treatments. Preliminary calculations have been performed for weak convection in A-type stars; a solar model soon to be studied will however be the sensitive test of the appropriateness of this approach in describing stellar convection.

Interstellar Medium and Galactic Astronomy: R. McCray and A. Dalgarno (Harvard College Observatory) have completed a detailed review of heating and cooling processes in the interstellar medium. McCray and J. Buff have shown that low-density, high-temperature HII regions in the galactic disk are likely to occur if the interstellar gas is heated by low-energy cosmic rays. McCray, and visiting scientists J. Swartz (Harvard College Observatory) and R. F. Stein (Brandeis University), have written a series of papers demonstrating that thermal instability in a cooling gas can cause the formation of HII condensations of 100:1 density contrast in interstellar HII regions, and also the formation of ionized filaments following a supernova outburst. They also have suggested that thermal instability might trigger the formation of protostars.

Dalgarno and McCray have examined various processes by which interstellar molecules may be formed by gas-phase reactions involving negative ions.

R. Lang and P. B. Bender considered uniformly pumped spherical models of OH 18-cm emission regions. An analytic approximation for the population inversion as a function of radius was found for the case of two levels, a square line shape, and heavy saturation at the center of the region. A simplified model for the 43.7 km/sec feature at 1665 MHz in the source W3 was constructed in which the actual size is 60 times larger than the apparent size.

The simple test-particle modelling by J. Toomre (with A. Toomre of MIT) of tidally interacting galaxies has suggested that a number of extended bridges and tails associated with peculiar galaxies may be the result of clear passage. Particle models have been constructed for Arp 295, M51, NGC 4038/9, and NGC 5676 approximately reproduce both the external shapes and some kinematic features of these objects.

D. L. Van Blerkom (University of Massachusetts), L.H. Auer (Yale University), and J.J. Castor have suggested an explanation for the anomalous polarization of the Hα radiation from the filaments in M82 in terms of resonance fluorescence.

Atomic and Spectroscopic Data: S. Geltman has evaluated free - free absorption coefficients for several electron-neutral atom systems with an estimated uncertainty of 30%. The wavelength range is 0.9 to 2 μm, the temperature range is 500 to 20000 K, and the atoms are He, C, N, O, Ar, Kr, and Xe.

R. H. Garstang has made an exhaustive survey of work which has been done on the calculation of atomic transition probabilities in various unusual coupling schemes; a synopsis of this will be included in a future book on spectral line intensities. Other work included an investigation of the effects of recent revisions of the laboratory energy level data on the transition probabilities of forbidden lines of Fe XIII.

D. G. Hummer and D. W. Norcross are engaged in a project of computation of electron excitation cross sections for the ions of C, N, O, and Si which are prevalent in early-type stars. This work will make use of the computer programs for the integro-differential equation and distorted wave approximations, and the related programs for atomic structure, developed by M. J. Seaton and his collaborators at University College, London. D. W. Norcross has developed a program for calculating photoionization, including the effects of autoionizing states, for ions with two electrons outside a closed shell. This program will be applied to those ions of the elements mentioned above which belong to the Bel and Mgt isoelectronic sequences. D. G. Hummer and J. J. Castor have computed energy levels of approximately one hundred bound and resonant states of CII in a multi-channel quantum defect theory in an attempt to identify the OI emission lines at λ4485, 4503.

J. Cooper, with C. R. Vidal and E. W. Smith (National Bureau of Standards), has prepared tables of normalized Stark broadened profiles of the first four Lyman lines and the first four Balmer lines of hydrogen. They are based on a "unified" theory of line broadening which covers the entire profile and should be especially accurate in the line wings. A theory which allows for nonstatic behavior of ions close to the forbidden components of Hε lines has also been worked out, in collaboration with E. W. Smith and A. J. Barnard (University of British Columbia), and tables are in preparation.

Continuing the work of the late J. C. Stewart, J. Cooper and J. M. Peck examined the broadening of Lyman α due to protons, and found "satellites" at 1233.5 and 1240.5 Å, which might be observed astrophysically. These satellites are similar to those found by Sando, Doyle, and Dalgarno for broadening of Lyman α by neutral hydrogen at about 1600 Å.
The work of A. Omont (University of Paris), E.W. Smith, and J. Cooper on the redistribution of resonance radiation has been extended to include a magnetic field. Although the formulae are quite complicated, it is possible to interpret the results of photolysis of a photon followed by a sequence of elastic (including m-mixing) redistributing collisions, with inclusion of the magnetic field, leading to an additional depolarization between the colliding partners.

F. Taylor and G. H. Dunn have measured the absolute cross sections as a function of energy for excitation of the C II H- and K-line electron impact. At threshold (3.1 eV), the cross sections are about 20% by the close-coupling calculations of Burke and Moores for this process. The polarization of the H- and K-line emission as a function of energy was also measured.

The electron excitation cross section for the neutral calcium resonance line at 4227 Å has been measured from threshold to 1500 eV by A. C. Gallagher. By normalizing to the Bethe approximation at high energy, where the measured energy dependence agrees with the theoretical, the total cross section (including cascades) is obtained with an accuracy of a few percent. The cross section rises very slowly just above threshold, causing rather small excitation rates at low temperatures, such as in the atmosphere of late-type stars where this line is very prominent. This behavior is in sharp contrast to that for excitation of the Na I D lines, reported earlier, for which the cross section rises very abruptly from threshold.

Cross sections for electron excitation of neutral hydrogen from the ground state with the production of Balmer- and Lyman-α radiation, have been measured by S.J. Smith with D. M. Cox and H. Mahan. Cox and Smith used rf pumping of the 2 3S 1 metastable state at the frequency corresponding to the Lamb shift, to determine the cross section for direct and cascade production of atoms in the 2 3S 1 state. A relative measurement of the Balmer-α excitation cross section by Mahan and Smith has shown that the cross section from threshold to 50 eV is generally 50% higher than indicated by the earlier measurements of Kleinpoppen and Krais.

Cross sections for photodetachment of three negative ions, O-, OH-, and C2 2-, have now been measured using a tunable dye laser by W. C. Lineberger, T. A. Patterson, and H. Hotop. The rates for the inverse process of radiative attachment, obtained from these cross sections by detailed balancing, are of considerable interest for the Dalgarano–McCarty theory of molecule formation in the interstellar medium.

IV. PUBLICATIONS

(Co-authors not connected with JLLA are shown in parentheses.)


J.C. Pecker, "Evolution Galactique. I. Effets"


