Joint Institute for Laboratory Astrophysics of the National Bureau of Standards and the University of Colorado, Boulder, Colorado

I. INTRODUCTION

The Joint Institute for Laboratory Astrophysics functions as a cooperative scientific venture of the National Bureau of Standards and the University of Colorado. Research conducted at JILA falls into several areas: astrophysics; aerodynamics; the physics of atomic collisions, both theoretical and experimental; spectroscopy and line broadening; chemical physics; and optical resonance phenomena.

Ten Visiting Fellows have been in residence at JILA during the year. They are: Benjamin Bederson, New York University; Dudley Herschbach, Harvard University; Sydney C. Haydon, University of New England, Armidale, N.S.W., Australia; Robert D. Hudson, Aerospace Corporation; Bodhan Paczyński, Polish Academy of Sciences; Richard N. Porter, University of Arkansas; Lindsey F. Smith, University of California, Los Angeles; Derek N. Stacey, University of Oxford; Pol Swings, University of Liege; Rafael Velasco, University of Madrid. Others working at the Joint Institute for extended periods during the year were George H. Herbig, Lick Observatory; Leonard Kuhn, University of California, Berkeley; and Peter Ulmschneider, Astronomical Institute, Wurzburg, Germany.

Post-Doctoral Research Associates included: William Baylis, Max Planck Institut; Donald R. Beck, Lehigh University; Radford Byerly, Jr., Rice University; John I. Castor, California Institute of Technology; Wayne Christiansen, Univer-
sity of California, Santa Barbara; Tom Delmer, University of California, La Jolla; Kenneth R. German, University of Michigan; Elizabeth L. Hallgren, York University, Toronto; Judah Levine, University of Oxford; William C. Lineberger, U. S. Army Ballistic Research Laboratories; Jeffrey Linsky, Smithsonian Astrophysical Observatory; James Mills, Brown University; Halia Odabasi, University of Colorado; and Christoph Ottunger, Harvard University; David Van Blerkom, University of Colorado; and Martin Vogler, Justus Liebig Universität, Giessen, Germany. An ESRO Fellowship supported the work of J. Pfleiderer from Bonn University.

During the year, 54 graduate students have been engaged in research at JILA. Five students completed their Ph.D. degrees: Dell O. Fystrom, George E. Langer, Louis J. Shramek, David Van Blerkom, and John C. Wheeler. Langer, Shramek, Van Blerkom and Wheeler all specialized in astrophysics.

Lewis M. Branscomb resigned as chairman of the Joint Institute effective 30 June 1969 to accept the position of Director of the National Bureau of Standards, Washington, D.C. Peter L. Bender was selected by the Fellows of JILA to be their new chairman. During the year, appointments to the staff were accepted by John J. Castor, Jeffrey L. Linsky, and George A. Sinnott. Regrettably, the Institute lost one of its Fellows through the untimely death of John C. Stewart.


Lists of JILA publications and reports may be obtained by writing to Mrs. Lorraine H. Volisky, Scientific Reports Editor, JILA, Boulder, Colorado.

II. Activity During the Past Year

As the range of activity in JILA is now too large to describe in the space available here, this report will be limited to astrophysical work and to that part of the atomic physics that is immediately relevant to astrophysics. Some information about other research results can be obtained from the list of recent publications at the end of this report.

Stellar Interiors and Stellar Evolution: Much of the work described in the last report has been completed or extended. In a study of the structure and pulsational stability of Mira variables, E. Langer has shown that the second mode is most unstable and that the second harmonic periods agree well with the observed periods. A qualitatively reasonable and self-consistent picture of their properties and evolutionary status has emerged from this study. K. Zielarth’s investigation of the pulsational stability and nonlinear pulsations of massive $(M > 60 M_\odot)$ main-sequence models is continuing and will culminate in his Ph.D. thesis. A long-range program of nonlinear calculations of Cepheid pulsations by J. Cox, D. S. King (University of New Mexico), and H. N. Cox (Los Alamos) continues to be active. A review paper on pulsating stars has been published by D. S. King and J. Cox.

B. Paczyński has evolved models with $0.8 \leq M/M_\odot \leq 15$ from the main sequence through hydrogen and helium exhaustion in the core to carbon ignition or the white-dwarf state. He has suggested that the presence of loops in the evolutionary tracks into the Cepheid region may result from thermal or secular instabilities at certain critical stages in their evolution. Following this suggestion of Paczyński’s, R. Sierig is investigating possible non-uniquenesses in stellar structure for models with more than one nuclear energy source.

W. Davey has developed a fast and efficient method of solving the linear adiabatic wave equation for spherically symmetric pulsations in stars and applied it to several stellar models. He has also investigated the phase delay in energy generation of the PPI proton chain in M dwarf models, in connection with their pulsational stability, and has shown it to be very small. At present, Davey is investigating the excitation of pulsations by gravitational contraction with a view to application to β Cephei and other types of variables.

J. C. Wheeler and J. J. Hansen have completed their investigation of the collapse and subsequent detonation of white dwarfs near the Chandrasekhar limit, in an attempt to explain type-I supernovae. They conclude that their earlier calculations were somewhat optimistic and they now believe the mechanism to be marginal or even physically unrealistic. Theoretical studies of the evolution of central stars of planetary nebulae by W. Deinzer and Hansen have been completed.

M. Herz, J. Cox, and Hansen have made considerable progress in a study of the characteristics of secular instability of stellar models in thermal and hydrostatic equilibrium. General programs, including both real and imaginary eigenfunctions and eigenvalues, have been developed and applied to homogeneous helium stars. A byproduct of this study is a set of helium “main-sequence” models with two luminosities for each mass. The only secularly unstable model found so far is located at the minimum mass of the sequence. Work is in progress on the inhomogeneous models derived from evolutionary calculations.
High-Energy Astrophysics: L. Oster has continued his studies of the Compton effect in astrophysical problems and has shown that scattering from the cosmic background radiation into the spectral region of the $3\hbar \nu$ radiation is negligible if current estimates of the cosmic-ray electron density are correct. He has also considered similar phenomena in the early stages of galactic phenomena and in very compact radio sources. In the latter case, the stimulated Compton component may well be the dominant one. Oster has also derived the equilibrium distribution functions of matter and radiation through the use of detailed balancing arguments. At very high temperatures the relations between the chemical potentials of elementary particles are obtained.

W. Christiansen has concentrated his efforts on the development of models capable of describing the general temporal evolution of large plasma clouds which comprise the primary regions of active radio emission in radio galaxies and some quasars. It is concluded that the observable lifetimes of radio galaxies are of the order $10^{18}$ to $10^{20}$ yr. Work currently underway entails the use of these models to provide theoretical descriptions of the observed spectra and brightness contours of radio galaxies.

J. Pfleiderer investigated a number of problems in the statistical mechanics of the classical electron gas permeated by magnetic fields.

Stellar Atmospheres and Spectral-Line Formation: The main emphasis this year was on the interpretation of spectra of Wolf-Rayet stars. This effort was an outgrowth of last year's symposium and was substantially aided by the presence here of L. F. Smith and I. Kuri. A series of "brainstorming" sessions on this topic stimulated a wide variety of activity, including the rejection of much of the folklore on these objects. Smith and Kuri are preparing an Atlas of Wolf-Rayet spectra, which will be completed shortly. J. Castor and D. Van Blerkom investigated the $H\beta$ spectra on the basis of a theory of line formation in expanding spherical envelopes that Castor had developed, and in collaboration with Smith investigated the effect of electron scattering on the profiles of certain lines.

J. C. Stewart and S. J. Hill have continued their investigation of the interaction between radiative energy transfer and the propagation of sound and shock waves in stellar atmospheres. R. N. Thomas and K. B. Gebbie have clarified the problem of determining the relative importance of the quality and the quantity of the radiation field in controlling the electron temperature in stellar atmospheres. Thomas also participated in the planning of the Symposium on Spectrum Formations in Steady, Non-Stationary Atmospheres, sponsored by Commission 36 of the IAU, where he gave an invited paper and chaired a session.

D. G. Hummer has completed a long investigation of various mechanisms causing frequency non-coherence in photon scattering and their effects on the radiation field in isothermal atmospheres and, with R. Shine, has begun to generalize these results to atmospheres in which temperature and density depend on depth. He has also solved the line-transfer problem with complete redistribution and dipole scattering, with the result that the radiation field differed little from the isotropic-scattering case. Hummer and G. Rybicki have extended their calculations of line formation in differentially expanding atmospheres to include temperature gradients and have increased considerably the speed of their computational method. D. Van Blerkom and Hummer have investigated the accuracy of a simple algebraic approximation to the solution of the line-transfer problem when the albedo is small.

J. Linsky has computed the pressure-induced opacity of molecular hydrogen which is of importance in late-type stars and, with D. Brown, has investigated statistical representations of the water vapor opacity for use in model-atmosphere calculations. S. J. Larson and Linsky have considered the possibility of observing deuterium in the form of HD in young main-sequence K stars and concluded that 10 to 100 times the terrestrial abundance of deuterium would be required.

Solar Physics: R. N. Thomas and K. B. Gebbie have analyzed the 1966 and 1967 eclipse data of J. E. Faller and S. R. Weart to determine the distribution of electron temperature in the region $10^3 < T_e < 10^5$, and are collaborating with Weart and H. Zirin of the California Institute of Technology in planning further eclipse observations at five points in the optical continuum. J. Linsky and R. Shine have investigated the temperature distribution in the same region using radio and infrared data obtained outside of eclipse together with eclipse data. Linsky has presented a method of obtaining more accurate radio brightness temperature measurements at millimeter wavelengths by using the moon as a calibration source. D. Brown and Linsky have considered the accuracy with which the solar temperature minimum may be inferred from the observed ultraviolet continuum when thermal fluctuations are important and the Eddington-Barbier relation breaks down. Linsky has proposed that the positive ion $H_2^+$ might account for the "mesing" opacity in the near ultraviolet, as the spectral and temperature dependence are about right. Unfortunately this ion is insufficiently abundant to provide the required opacity.

Linsky has reduced his observations of the $H$ and $K$ lines obtained at Kitt Peak and finds a steeper thermal gradient rather than increased density in plages. In reviewing the interpretation of the pro-
files he has concluded that relaxing the assumptions of hydrostatic equilibrium and complete redistribution lead to better agreement between theory and observation. Linsky, R. G. Teske, and C. W. Wilkinson have presented observations of the Ca II infrared triplet on the solar disk which can be explained only by including inhomogeneities in the lower chromosphere.

The JILA-High Altitude Observatory-Sacramento Peak summer program for students in solar physics was reactivated and ten students spent a fruitful summer at Sacramento Peak. R. N. Thomas and K. B. Gebbie have been collaborating with E. U. Condon and H. A. Gebbie in planning a far-infrared observatory on Pikes Peak.

Planetary Nebulae: D. Van Blerkom has completed his investigation of the anomalous H I, He I, and He II recombination spectra in planetary nebulae. Although a number of possible mechanisms were investigated in detail, no conclusive solution to this problem could be found. However, inconsistencies in the observational material were noted. Van Blerkom and D. G. Hummer discussed the possibility of recombinations of positive ions with electrons in surface states of dust particles.

Hummer and D. Mihalas (Yerkes Observatory) have completed their calculation of 70 model atmospheres for the central stars of nebulae. Considerable attention was given to the dependence of the flux distribution on composition and gravity. Hummer is now redetermining the empirical H-R diagram for these objects using the model results along with new observational material.

Atomic Physics and Spectral-Line Broadening: R. H. Garstang made a study of magnetic quadrupole radiation in highly ionized atoms in which he showed that transitions of the form $^3S_0 \rightarrow ^3P_1$ can occur and may be important de-excitation processes in Fe IX, Fe XVII, and Fe XXV in the solar corona, while such transitions in Fe XV and Fe XXIII are probably unimportant. L. J. Shames and D. R. Beck adapted a Hartree-Fock program to the local computer and initiated calculations of certain quadrupole transitions in Ar I which may be observable in the laboratory. T. Delmar investigated configuration interaction in the P I spectrum in an attempt to calculate transition probabilities in that spectrum.

J. C. Stewart has evaluated the proton-broadening contribution to the wing of the Lyman-alpha profile, including all orders of the Stark effect and electron tunneling, through the use of Bates' exact H I energies. The profile is substantially altered from Holtsmark's result and shows two "satellite" lines in the red wing.

J. Cooper has been involved in a considerable number of projects leading to a vastly improved knowledge of collision broadening in situations of direct interest to astrophysicists. Much of this work has been done in collaboration with E. W. Smith and C. R. Vidal of NBS, W. Chappell of the University of Colorado, and G. K. Oertel of NASA. Profiles of strong He I lines and their forbidden components arising from Stark broadening have been calculated accurately by A. J. Barnard, Cooper, and Shamey. Results have been published for the He I $\lambda 4471$- and 4922-Å lines and subsequently these results have been extended to larger wavelength displacements, to lower electron densities, and to other lines. Stark broadening in hydrogen has been re-examined in detail and a more consistent treatment of electron correlations and strong collisions has been developed, leading to a unified treatment of the hydrogen lines which makes neither impact nor quasi-static approximations and which agrees remarkably well with experiments. Further work on correlations between collisional and Doppler broadening, which is relevant for Van der Waals broadening, and on resonance broadening is underway. Some improvements to the theory of Stark broadening of isolated lines have been made. Experimental results for the Stark broadening of certain Na I lines have been obtained by P. E. Oettinger and Cooper and experiments on Van der Waals broadening from neutral hydrogen are underway. Finally, a heat-pipe oven which provides an ideal oven for the experimental determination of oscillator strengths of metals has been developed by Vidal and Cooper.

III. Publications

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


A. J. Barnard, J. Cooper, and L. J. Shames, "Calculated Profiles of He I 4471 and 4922 Å and their


P. E. Oettinger, "Combination Oven-Linear Pinch


(H. Friedrich) and E. Trefftz, "Semiempirical Potentials for Some Atomic Core: C\textsuperscript{+}, N\textsuperscript{+}, O\textsuperscript{+}, Mg\textsuperscript{+}, Al\textsuperscript{+}, Si\textsuperscript{+}, Ca\textsuperscript{+}, Ba\textsuperscript{+}," J. Quant. Spectr. Radiat. Transfer 9, 245 (1969).


