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10 January 1973

Ms Beverly J. Hungerford
Grant Administrator
National Aeronautics and Space Administration
Washington, D.C. 20546

Dear Ms. Hungerford: Re: NGR 07-004-004

Enclosed are two copies of a final technical report for the NASA grant NGR 07-004-004, prepared by Rupert Wildt, principal investigator. [illegible]

Sincerely yours,

Mary S. Albee

Mary S. Albee for
Rupert Wildt

encl:

cc: J. S. Warner

(NASA-CR-130792) [LOCAL THERMODYNAMIC EQUILIBRIUM IN STELLAR ATMOSPHERES] Final Technical Report (Yale Univ.) 4 p HC $3.00 CSCL 03B

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Final Technical Report - NASA Grant No. NsG 82-60 (07-004-004)
by Rupert Wildt
Yale University

The motivation behind all the work carried out under this grant was the logical dilemma posed by the assumption of Local Thermodynamical Equilibrium (LTE) in stellar atmospheres, and the realization that the problem must be placed in the larger context of irreversible thermodynamics. Two fundamentally differing approaches to a tentative solution were tried.

At my request, Mr. Myron Lecar investigated by elaborate numerical computations "Departures from Local Thermodynamical Equilibrium in an AO Star Atmosphere" and in 1962 presented this work, in form of a dissertation in candidacy for the Ph.D. degree, to the Faculty of the Graduate School of Yale University; he received the degree in due course. This dissertation, which remains unpublished, is on file in Yale University Library. Mr. Lecar's principal results were as follows. By comparison with an accurate model, departures from LTE were evaluated for model atmospheres in radiative equilibrium approximating an AO star (pure hydrogen, $T_{eff} = 10^4$, $g = 10^3$ and 10^4 cm sec^{-2}). The non-LTE atomic populations depress the emergent flux in the Lyman continuum and in the lines by 10-30%, but the Balmer and higher continua are unaffected. Thus the temperature stratification is unchanged. At the surface, the lowest three bound states are overpopulated, the higher bound states are underpopulated, and the degree of ionization is reduced by a factor of two with respect to LTE. The populations converge to their LTE values at optical depth two. The steady-state populations are unchanged by increasing the collisional rates by a factor of 100 or dropping them altogether. Mr. Lecar's pioneering work has been continued and improved upon, first at the Smithsonian Astrophysical Observatory, and later by many investigators other places, including Yale.

The second approach was the attempt of the Principal Investigator to gain physical insight into the transfer of radiation through the classical gray model atmosphere by analytical methods. The results form a series of papers published in the Astrophysical Journal under the common title "Thermodynamics of the Gray Atmosphere", and can be summarized as follows.

I. (Ap.J. 140, 1343, 1964). For every pencil of radiation inside a gray atmosphere in strict radiative equilibrium, energy spectra characteristic of different net fluxes (effective temperatures) are linked by a certain similarity transformation if the source function, which need not be Planckian, undergoes the same transformation. Related transformations hold for the concomitant variations of the spectra of radiant entropy. The common physical correlates of these similarity laws are quasi-statical processes taking the radiation field of the gray atmosphere, i.e. a non-equilibrium system from one steady state to another. Because they satisfy all appropriate criteria, it is well within the bounds of accepted usage to call them reversible adiabatic processes, a term that classical thermodynamics had reserved for passages through a sequence of equilibrium states.

II. (Ap. J. 143, 363, 1966). In a gray atmosphere in local thermodynamical equilibrium all pencils of radiation are bluer than equilibrium radiation of matching total energy; and the divergence of the net flux of photons is positive at all depths - to the effect that radiation transmitted suffers cumulative reddening and that the rates of inverse atomic processes of interaction between gray matter and off-equilibrium radiation cannot balance. The unattainability of detailed balancing conforms to principles of kinetics (Einstein relations, etc.) holding irrespective of grayness. While under non-gray conditions it would be difficult to ascertain the sign of the divergence of the photon net flux, a sufficient condition for its positivity in the gray case is the monotone approach to asymptotic thermodynamic equilibrium at great depth.

III. (Ap.J. 146, 418, 1966). The total entropy of a pencil of non-equilibrium radiation falls short of the entropy maximum associated with equilibrium radiation with the same total energy as that of the pencil (entropy defect of non-equilibrium radiation). For the source function an entropy defect can likewise be defined, and its integral over the entire atmosphere, called "global entropy defect", affords a measure of the over-all departure from local thermodynamic equilibrium. In a gray atmosphere, minimizing the global entropy defect of the source function with proper constraints, generates the spectrum of a source function conforming to the non-degenerate case of Bose-Einstein statistics. It attains at the surface the maximum departure from a Planck function, to which it tends monotonically with increasing optical depth.

To sum up, Dr. Lecar's work for the first time established the existence and magnitude of deviations from LTE in the atomic populations in a well-defined and non-trivial model atmosphere; and the analytical work on the gray atmosphere culminated in the derivation (from a variational principle) of a source function for the continuous spectrum that can be called realistic, in the sense that it reaches the maximum deviation from LTE at the stellar surface and goes smoothly to LTE at infinite depth.