JUN 16 1964

STELLAR OPACITIES

Arthur N. Cox

82111

MASTER

In 1926, Eddington wrote a book on stellar structure which collected the then known information about stellar interiors. The book titled "The Internal Constitution of the Stars" showed that stars transport energy from the hot interior primarily by radiation instead of by convection as was previously assumed. The importance of radiation transport, discussed from time to time since before the beginning of this century, is based on the fact that the radiative opacity of stellar material is usually low enough so that energy coming from the interior does not have to be carried by convection or conduction.

A more comprehensive discussion of stellar structure has been given by Walter K. Bonsack in "Stellar Interiors" Leaflet 374 in August 1960. In this article only the details of radiation flow are discussed, and reference to the previous leaflet shows how this story fits into the descriptions of the many forms of stellar interiors.

In the very deep layers of a star, very "hard" photons called X-rays carry the energy by a diffusion process. These photons travel only about one centimeter before they are absorbed by the hot stellar material. The hot gas then reemits photons of all energies in a distribution depending only on its temperature. Absorptions, scatterings and emissions depend on the composition, temperature, and density of the stellar matter as well as the photon energy and travel direction, and are governed by a so-called equation of transfer. For stellar atmospheres the complete

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:
 A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
 B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.
 As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

This paper was submitted for publication in the open literature at least 9 months prior to the issuance date of this Microcard. Since the U.S.A.E.C. has no evidence that it has been published, the paper is being distributed in Microcard form as a preprint.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

equation of transfer is required to describe the structure. However in the diffusion (stellar interior) case where the photons travel very small distances compared to the scale of temperature changes, the elaborate equation of transfer can be reduced to a simple form involving only the matter temperature, density and opacity. This opacity for the photon diffusion is an average over the absorptions for all the photon energies.

Rosseland in 1924 derived the photon diffusion formula and showed how to take the average of the absorptions for photons of different energies. This Rosseland mean is used extensively in studies of stellar structure as well as in other terrestrial cases where the diffusion approximation is valid.

Quantitative calculations of the Rosseland mean opacities date back to the work of Ström["]gren in 1932. Opacity calculations involve knowledge of the detailed absorption processes, but they result in values of the opacity which depend only on the material composition, temperature and density. Actually the opacity "law" can be written as a very simple formula if one does not want to worry about high accuracy.

Numerous workers have been involved in calculations of opacities since Ström["]gren, and the result has been an ever growing list of opacity tables. Since the exact structure and evolution of a star depends on the opacity, modern precise work requires tables for compositions ranging from pure hydrogen to mixtures supposed to represent interiors of very highly evolved stars.

All opacity calculations have relied on the theory of atomic structure to give the interaction details of matter and radiation. The most important absorption process in stellar interiors is usually the bound-free

or photoelectric ejection of an orbital (bound) electron from an atom or ion. This is a threshold interaction because the incoming photon or X-ray must have at least enough energy to tear off the bound electron from its attracting atomic nucleus. Any additional energy the photon may have can be used by the electron as kinetic energy. The laws of atomic physics and quantum mechanics show that the bound-free absorption is largest just at or very near the absorption "edge" where the electrons are just barely liberated. For harder photons the probability of an absorption decreases very rapidly. Bound-free absorption also depends on the equilibrium "occupation numbers" or the number of bound electrons in the various atomic energy levels of all the ions present.

A second, usually important, mechanism of photon absorption is by the free-free process. In this case the photon interacts with a free electron which is in the field of a charged atomic nucleus. The free orbit of the electron is changed to one of higher energy and the photon disappears. The efficiency of this absorption depends on the density of free electrons and on the density of the nuclear charges. Unlike the bound-free absorption, there is no threshold for this photon absorption and the lowest energy photons may be absorbed by this process alone.

Photons can be scattered or changed in their travel direction by free electrons which may also change the photon energy somewhat. This scattering affects the transport of energy by photons. It is unlike true absorption because the photon does not disappear though it may be reduced in energy. The effects of the low photon energy (Thomson) or the high photon energy (Compton) scattering must also be included in opacity calculations.

Absorption can take place by using a photon to move a bound electron from a low bound energy level to a higher level. This absorption is rapidly varying with photon energy. Only particular energy level spacings occur in ions, and only between the levels are absorptions allowed. Even though the absorption occurs over very narrow values of photon energy, in some cases the stellar material may have many lines of different ions and elements superimposed to give very high absorption. At about 10^5 °K and 10^{-4} gm/cm³, the line absorption can triple the stellar material opacity over its value without the lines.

Very near the stellar surface, electrons from the easily ionized metals combine with neutral hydrogen or molecular hydrogen to form H^- or H_2^- . The bound-free and the free-free (hydrogen atom and free electron) absorptions of H^- and the free-free absorption of H_2^- influences the appearance of the emergent radiation from stars like the sun. It is important to include the negative hydrogen in opacity calculations at temperatures below about 15,000°K at normal stellar atmosphere densities.

Photons are also scattered by bound electrons in the lowest energy level of an ion. An electronic jump to the next higher level is usually followed by a jump to the lowest level again with reemission of the same energy photon travelling in a different direction. Even though this scattering is about as effective as the line absorption, it occurs usually only in the so-called resonance lines. A special scattering of low energy photons is called Rayleigh scattering. Scattering by bound electrons is important in opacity calculations only at the temperatures of stellar surfaces.

Additional processes involving the absorption by neutral or ionized hydrogen to form molecular hydrogen may also contribute to the opacity of stellar atmospheres.

The calculation of opacities involves first utilization of the laws of ionization and excitation. When the degrees of ionization of all the elements, negative ions and molecules, the occupation numbers in the bound states, and the density of free electrons are known, then one has what is called the equation of state. Other equation of state properties such as pressure, entropy, etc. can then readily be computed. At each photon energy, the absorption and scattering by all the above processes are added to give a monochromatic absorption coefficient. A final averaging over photon energy (frequency) is then done to obtain the Rosseland mean opacity.

Graphs showing the opacity for a typical stellar mixture in the unit cm^2/gm versus temperature for several densities are given in the figures. It is seen that the value of the opacity does have a regular behavior which can be approximated by simple laws if high accuracy is not required.

Even though opacities and monochromatic absorption coefficients are available for many mixtures, more data are still required. Also improvements in a number of technical details are necessary to assure data of the highest accuracy. Such improvements are very desirable because upon these stellar opacities rest an understanding of the many details of stellar structure and evolution.

Fig. 1. - Line opacities versus temperature for various densities.
Lower opacities.

Fig. 2. - Line opacities versus temperature for various densities.
Higher opacities.