This Week's Citation Classic®

Cox D P & Tucker W H. Ionization equilibrium and radiative cooling of a low-density plasma. *Astrophysical J.* 157:1157-67, 1969.
[Physics Dept., Univ. California, San Diego, CA; Space Science Dept., Rice Univ., Houston, TX]

This paper presents the proportion of each element in its various stages of ionization for cosmically abundant elements in a high-temperature, optically thin plasma, assuming equilibrium between collisional ionization and recombination rates. It further calculates the contribution of each element to collisionally induced radiation and, summing those for normal (solar neighborhood) abundances, the net radiation rate of the plasma. The useful temperature range is 10^4 to 10^8 K. [The *SCI*® indicates that this paper has been cited in over 395 publications.]

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These results were needed before I could do the problem set by my thesis advisor at the time, W.L.W. Sargent, at UC San Diego. He wanted the spectrum of an interstellar shock wave for comparison with spectra of the Cygnus Loop. The biggest part would be calculation of the ionization structure and radiation rate of the plasma. Sargent suggested I talk with Wally Tucker, who was a student working with Bob Gould. The latter two began my education in collisional processes in 1965-1966. Under Wally's tutelage, I began compiling energy levels and rates.

The following year, Sargent moved to Caltech, Tucker to Cornell, and I to UCLA. Sargent had made arrangements with Lawrence Aller to look after me for the year while I learned some astronomy and caught up with my UCSD classmates in physics (I had been an electrical engineering major). Aller and UCLA provided a wonderful environment, and the compilation went on. I learned to invent data that had never been measured or calculated. Wally's influence was now more remote but consistently useful.

The following year, I returned to UCSD, Tucker moved to Rice, Sargent stayed at Caltech, and William Mathews became my new research advisor. Bill was full of ideas and it was a lively time, but I was able to continue my original project. Once the data compilation (and invention) were complete, it was easy to calculate both the total radiation rate of a plasma for given ionization structure and the ionization structure in idealized cases. In the *Citation Classic* article, Wally and I published the results described in the abstract above. I then went back to the radiative shock-wave problem that constituted the main thrust of my thesis, and Wally moved to the American Science and Engineering company in Boston, where he continued doing landmark work in the burgeoning field of high-energy astrophysics.

In 1972 I attended a lecture during which the speaker, Kevin Prendergast, said something I didn't understand. Later I cornered him to ask about it. "Oh," he said, not knowing me, "you don't understand because you don't realize that the cooling rate for a plasma turns over at high temperatures." It was my first real clue of the pervasive importance of what Wally and I had done.

Until that time, most astronomical work on hot plasmas concerned itself with the optical spectrum of photoionized plasmas with temperatures around 10^4 K. We extended the theoretical basis to much higher temperatures and collisionally ionized plasmas. This was coincident with a rapid growth in UV and X-ray astronomy, and the results were very useful for making estimates of cooling rates in newly observed environments. Information of the same sort was needed for studying losses in laboratory plasmas, and our work provided background for those applications.

Since our paper appeared, this area of investigation has become an established effort with a number of useful contributors.[1] Many of the needed collision cross-sections have been calculated or measured, estimated abundances of elements have changed, previously ignored processes have found recognized importance, and time-dependent ionization structure has been included for a number of interesting cases. For useful applications, one needs, not a graph in a published article, but rather a computer code that is continuously revised in light of the most recent developments. A number of such codes are now maintained in the US and abroad. The direct Gould-Tucker-Cox legacy lives these days in John Raymond at the Smithsonian Astrophysical Observatory. As a student of mine in Wisconsin, he proved better than I at the skills required to keep this program developing (see bibliography in reference 2).

1. Arnaud M & Rothenflug R. An updated evaluation of recombination and ionization data. *Astron. Astrophys. Suppl. Ser.* 60:425-57, 1985.
2. Cox D P & Raymond J C. Preionization-dependent families of radiative shock waves. *Astrophysical J.* 298:651-9, 1985.

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