7. Laboratory Determination of the Luminous Efficiency of Meteor Constituents

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A crossed beam apparatus has been used to measure the emission and ionization cross sections for the prominent spectral features of Na, Ca, Mg, and Fe in collisions with N_2 and O_2 over the velocity range of 30 to 120 km/s. From the emission and ionization cross sections, the absolute luminous efficiencies in air were determined over the range of meteor velocities. The maximum luminous efficiencies for the brightest features were: greater than 1 percent for the Na D-lines, 0.2 percent for the CaI(2) singlet, 0.06 percent for the MgI(2) and MgI(3) triplets, and 0.4 percent for Fe over the visible spectral range. These luminous efficiencies are valid for free molecular flow conditions for velocities above about 30 km/s and are directly applicable to spectroscopic observations of faint meteors. The luminous efficiency of a typical stone will be presented and compared with the efficiencies determined by other investigators. In contrast to previous work, the luminous efficiency found for stone in the present investigation decreases with velocity above about 50 km/s.

METEOR LUMINOSITY RESULTS primarily from the excitation of vaporized meteoric constituents during decelerating collisions occurring with atmospheric molecules. The naturally occurring process of meteor vapor excitation during the cascade of energy-transferring collisions can be simulated in the laboratory by observing the emission probability under controlled single collision conditions and integrating over all collisions to obtain the total radiating efficiency.

The major aim of our research at Ames Research Center is to make appropriate laboratory measurements of the light emissions due to collisions between air molecules and typical meteoric atoms to allow for a direct calculation of the spectral luminosity of meteors. The efficiency of converting kinetic energy to luminous energy is the luminous efficiency, τ, and for a particular spectral feature the two are related by

$$I_\lambda = -\tfrac{1}{2}\tau_\lambda v^2 \frac{dm}{dt}$$

where v is the meteor velocity, dm/dt is the mass loss rate of the element and λ is the wavelength of the spectral feature.

The spectral luminous efficiency for free molecular flow conditions can be determined from the relationship given by Sida (1969)

$$\tau_\lambda = \frac{2E_\lambda}{E_0} \int_{E_t}^{E_0} \frac{\sigma_\lambda}{\sigma_m} \frac{dE}{E}$$

where E_0 is the initial kinetic energy, E_λ is the photon energy, E_t is the threshold energy for exciting the wavelength λ, σ_m is the momentum transfer cross section, and σ_λ is the cross-section for the emission of a photon of wavelength λ in a collision between an air molecule and a meteor atom. The mathematical formulation of τ in slip

flow is too complex for present analysis and will not be considered here.

An appreciable fraction of the ablated meteor atoms is expected to be ionized during the deceleration process. The ions formed can produce either ion lines or, if neutralization occurs, neutral lines upon subsequent collisions. Therefore, an accurate determination of τ_λ must take into account the fraction of ions present during the deceleration process. The luminous efficiency equation can be evaluated using an effective emission cross section given by:

$$\sigma_\lambda(E) = \sigma_{\lambda i}(E) \frac{N_i(E)}{N_0} + \sigma_{\lambda n}(E) \left[1 - \frac{N_i(E)}{N_0}\right]$$

where $\sigma_{\lambda i}(E)$ is the emission cross section for collisions of ions with air molecules and $\sigma_{\lambda n}(E)$ is the emission cross section for those collisions involving neutral metal atoms. The ion concentration generated in decelerating the ablated atoms from initial energy E_0 to energy E can be found from the relation $N_i(E)/N_0 = 1 - e^{-\beta(E)}$ where the ionization probability $\beta(E)$ is determined from the relation given by Sida (1969)

$$\beta(E) = 2 \int_E^{E_0} \frac{\sigma_i}{\sigma_m} \frac{dE}{E}$$

where σ_i is the ionization cross section. Finally, the measurable quantities in our experiments, which are related to σ_λ and σ_i, are the number of photons and ions produced in the collision of a beam of N_2 or O_2 with a perpendicular beam of metal atoms. The definitive relationship for these cross sections is $\Phi_\lambda = F(1 - e^{-Nx\sigma_\lambda})$, where Φ_λ is the number of photons per second emitted at a wavelength λ when a gas beam of intensity F passes a distance x through a metal beam of density N. A similar expression relates σ_i to the number of ions produced.

APPARATUS

The crossed molecular beam apparatus used to make these measurements shown in figure 1 has been described in detail in our previous reports (Boitnott and Savage, 1970; Savage and Boitnott, 1971). Briefly nitrogen or oxygen is ionized in the source and focused through the analyzing magnet to select the desired ion. The ion energy is set by
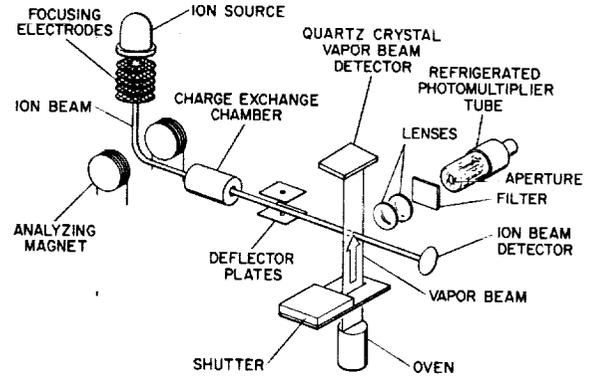
FIGURE 1.—Schematic of emission cross-section apparatus.

the potential at the ion source. The resulting N_2^+ or O_2^+ beam is then focused into a charge exchange cell which contains enough N_2 or O_2 to resonantly charge exchange about half of the original ion beam. In such a charge exchange process, there is no energy exchange or scattering as long as the densities are low enough so that there are no secondary collisions. The electrostatic deflection plates remove the remaining ions from the beam leaving only N_2 or O_2 to be injected into the test chamber. Intersecting at right angles to the N_2 or O_2 beam is the metal atom beam which emanates from a slit in an oven (the flux of metal atoms being determined by the oven temperature). The measurements were generally made with metal atom densities of the order of 10^{10} cm^{-3} while the background density of gas in the test chamber was about 5×10^{10} cm^{-3}. For Na, the flux was measured with a hot tungsten oxide surface ionizer as described in our Na paper (Boitnott and Savage, 1970); and the Mg, Ca, and Fe fluxes were measured with an oscillating quartz crystal.

A portion of the photons generated by the collisions pass through a bandpass filter and are counted. The bandpass of these filters is typically 100 Å and is centered on the multiplet of interest. Now, with the photon count, calibration factors, metal atom density, and gas beam intensity, the emission cross section is determined. Then with the ionization cross section determined from the ion count, we can work through the equations previously discussed and determine the luminous efficiency for the spectral feature being observed.

The conditions of the experiment which can be controlled are:

(1) The densities of the colliding beams
(2) The energy involved in the collision
(3) The collision partners
(4) The photon wavelength observed.

In regard to the densities of the beams, all of our measurements have been made under free molecular flow conditions. As for the energy, unfortunately, our lowest energy is limited to about 150 eV so that the luminous efficiency calculations must be made with extrapolation of the pertinent cross sections. Therefore, the efficiency values below about 30 km/s are much more uncertain than at the higher velocities.

EMISSION CROSS SECTIONS

The emission cross sections of the most prominent multiplets of Na, Mg, and Ca are shown in figure 2 over the range of energies investigated. The wavelengths of the lines of each multiplet shown in figures 2, 3, and 4 are listed in table 1. The data shown for Fe are for the total radiation in the wavelength range between 3500 and 4200 Å. The number of lines in the Fe spectrum is so numerous and closely spaced that bandpass filters could only make measurements for collections of multiplets and could not easily isolate individual multiplets. At wavelengths greater than 4200 Å, the blackbody radiation from the

source oven made meaningful measurements very difficult.

Cross sections for Mg and Ca shown in figure 2 are typical with other multiplets of these elements
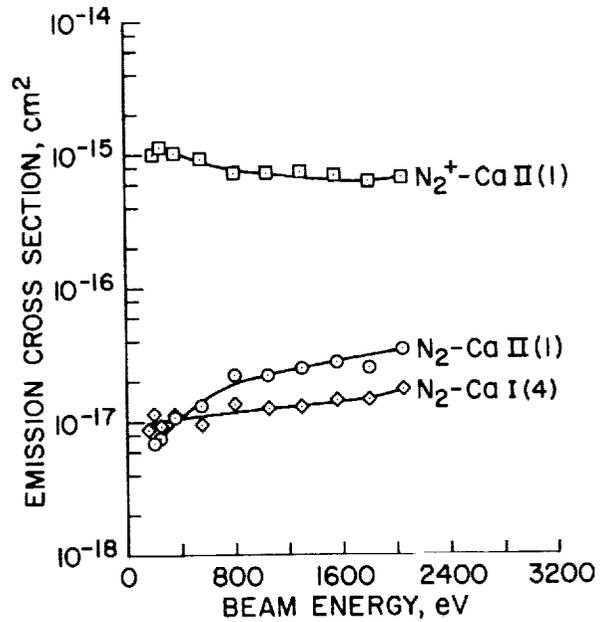
FIGURE 3.—Emission cross sections of Ca due to N_2 and N_2^+ collisions.

FIGURE 2.—Emission cross sections due to N_2 collisions for the prominent multiplets of Na, Mg, and Ca and of Fe over the range 3500 to 4200 Å.
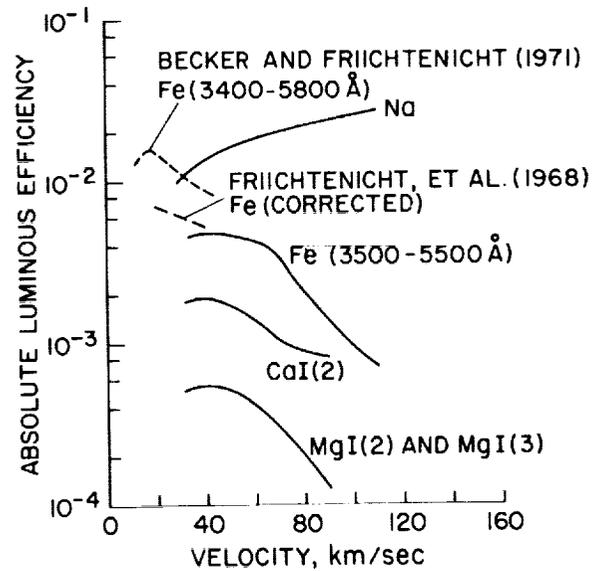
FIGURE 4.—Absolute luminous efficiencies for the prominent multiplets of Na, Mg, and Ca and of the visible spectrum of Fe.

TABLE 1.—*Wavelengths of Multiplet Lines*

Multiplet	Line wavelengths, Å
Na D-lines	5890, 5896
CaI(2)	4227
CaI(4)	4425, 4435, 4455
CaII(1)	3934(K), 3938(H)
MgI(2)	5167, 5173, 5183
MgI(3)	3829, 3832, 3838

showing similar characteristics but with smaller magnitudes. Collisions involving O_2 instead of N_2 generally had lower cross sections, by as much as a factor of 5, and did not necessarily show the same variations with energy (Savage and Boitnott, 1971; Boitnott and Savage, 1970).

Of considerable interest are the CaII(1) lines, H and K, since they frequently appear enhanced in meteor spectra and are thought to indicate slip flow conditions. The emission cross sections are shown in figure 3 as a function of energy for both N_2 and N_2^+ in collisions with neutral Ca. In addition to the large difference in magnitude between the ion and neutral collision partners, the variation with energy is completely different. The high H and K emission for N_2^+ collisions with neutral Ca is due to near resonant charge exchange including excitation of the Ca ion in a single collision. Without getting into a complete discussion of the H and K line enhancement as the meteor gets lower in the atmosphere, we want only to show that even in the free molecular flow regime there is considerable H and K emission as a result of neutral-neutral collisions. For the luminous efficiency and a more complete discussion of the H and K enhancement, see Boitnott and Savage (1971). The cross sections indicate, that in the free molecular flow regime, the multiplets CaI(4) and CaII(1) should be of nearly equal intensity. Any enhancement of the H and K lines should take place as the meteor enters the denser atmosphere where there are secondary collisions between neutral calcium and metal or gas ions, i.e., slip flow conditions.

LUMINOUS EFFICIENCIES

The absolute luminous efficiencies for the most prominent multiplets of Na, Mg, and Ca are

shown in figure 4 along with the total luminous efficiency for the visible spectra of iron. For the luminous efficiencies of the other multiplets of Mg and Ca, see Boitnott and Savage (1971). To obtain the total for iron, allowances were made for the visible spectrum above 4200 Å by comparing our bandpass data in the 3500 to 4200 Å range with the spectrum obtained by Tagliaferri and Slattery (1969) and with the natural meteor data of Harvey (1970). The decrease in the efficiencies of Fe, Mg, and Ca at the higher velocities is caused by the high relative probability of ionization at these velocities. This has the effect of removing neutral atoms which might be excited during a later collision in the deceleration process. Also the emission cross sections for the neutral atom lines due to collision between metal ions and air molecules are very low in comparison to those for neutral-neutral collisions. There is generally good agreement between our data and the free molecular flow meteor simulation experiments of Friichtenicht et al. (1968) and Becker and Friichtenicht (1971). The data of Friichtenicht et al. has been increased by 20 percent to account for the more accurate spectral distribution found later by Tagliaferri and Slattery (1969).

The luminous efficiencies we have determined for the multiplets of Na, Mg, and Ca and the
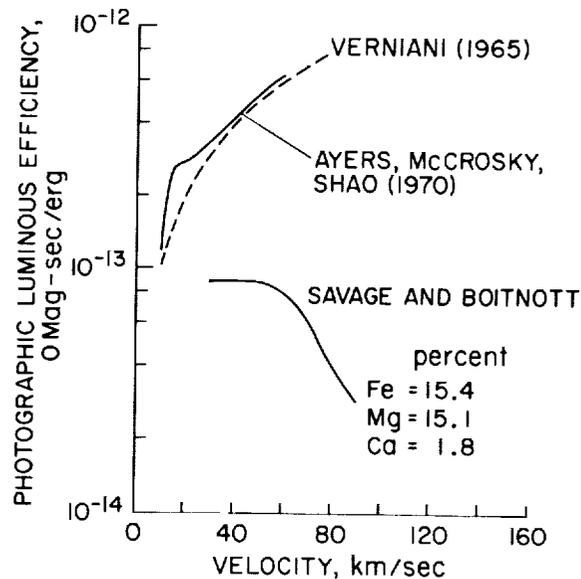
FIGURE 5.—The photographic luminous efficiency of a stone for blue sensitive film.

total for iron are directly applicable to the determination of the relative abundances of these elements in those free molecular flow photographic meteors for which good resolution spectra are available. With an assumption on the relative abundances of the weak and nonradiating elements which make up the rest of the meteor, the mass can be determined.

As an exercise, we have calculated the photographic luminous efficiency of blue sensitive film (Ayers, 1965) for a meteor with the assumed composition of meteoric stone (fig. 5). Variations in the composition would have only minor effects on the magnitude of τ without changing the general trends. Other vaporized elements present in the meteor are assumed to provide negligibly weak radiation and are neglected. In addition, any contribution by air molecules is not included in the calculations. Such radiation is toward the red and is seen in spectra using panchromatic film as are the Na D-lines.

For comparison, we show the luminous efficiency deduced by Verniani (1965) from 413 photographic meteors where he assumed that τ is proportional to the V^n, for all velocities, and concluded that $n = 1$. Also shown is the best guess efficiency of Ayers et al. (1970) which is primarily based on low velocity, near continuum flow, artificial meteor data. The reasons for the large differences are not clear to us at this time.

In summary, we have measured in the laboratory the fundamental emission and ionization cross sections needed to determine the spectral luminous efficiencies of Na, Mg, and Ca and the total efficiency for iron. We are encouraged by the good agreement with the luminous efficiency of iron measured by Friichtenicht et al., and Becker and Friichtenicht, and feel that the luminous efficiencies obtained can be applied to the quantitative analysis of meteor spectra in free molecular flow conditions.

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