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TEMPERATURE PROFILES OF IMPACTS

Gregory H. Canavan

Similarity solutions determine the profiles of density and temperature from impacts, which determine the scaling of the temperature and optical depth on material parameters, time, screening, and impactor size.

This note uses scaling results derived earlier for the growth,¹ size,² and temperature³ produced by impacts to discuss the radial temperatures profiles they produce. While the plasmas cool in milliseconds, they offer unique information about the thermodynamic state and material properties of the target material. The brightness temperature can be estimated from known two-dimensional similarity solutions. Regions close to unit optical thickness contribute effectively to the radiation, hence, they determine the plasma brightness temperature. The estimates of temperature as a function of time can be combined with the estimates of the exit hole size to estimate the total observable signal, which should be readily observable from distances of hundreds of kilometers.

The specific energy of the plasma produced by impact is determined by the velocity of the impactor; for impact velocities on the order of 10 km/s, this gives initial temperatures on the order of 1-2 ev. Similarity solutions are available for the subsequent flow, although they are complicated by the irregular impactor and target and unknown shape and composition of the target, equation of state, and preexisting fractures. Similarity solutions determine the temperature and density profiles of the blow off plasma, and hence the local and integral absorption to a surface in the plasma. The radiation comes from the surface with unit optical thickness. As time since impact increases, the surface moves further from the target and the brightness temperature falls slowly. The flow diverges after it reaches a distance from the body roughly equal to the impact's diameter. Thereafter, the density and temperature fall more rapidly than the solutions for the original one dimensional expansion, which fixes the unit optical depth surface at a distance about $2/3 D$ from the target, fixing the temperature profile and exposing a slightly higher brightness temperature than would be visible through the thicker 1-d plume. Sensitivity to the surface temperature is strongly reduced by thick plumes. However, for very small impactors the plumes are thin, and it is possible to observe the surface temperature directly.

Background. The specific energy of the plasma produced by the impact of an object at speed V is $\approx V^2/2$. For impact velocities on the order of 10 km/s, this gives initial temperatures on the order of 1-2 ev,⁴ although they fall on the time scale of hydrodynamic expansion, which is about 30 cm / 10 km/s sound speed ≈ 30 microseconds, during which the debris both expands as a shock into the surrounding material and flows out the entrance hole, which affords an

opportunity to observe the luminous material and infer the material properties of the target material. The treatment of impact process is complicated by the irregular geometry of the impactor and target, the unknown shape and composition of the target, and the unknown equation of state and preexisting fractures in the target. However, it is possible to make scaling models of the interaction adequate for the formulation of estimates.

Impact. The simplest model estimates the brightness temperature of the material in the impactor entrance hole from similarity solutions of the partial differential equations for two-dimensional impacts. They produce several robust predictions, the most important of which is that the flow out the entrance hole is essentially an isentropic expansion from unloading behind the shock. The second is that in very high-speed impacts, the bowl-shaped cavity is large and roughly spherical, and the entrance hole is large, but only about two percent of the mass escapes through it, because the density of the material in the hole is only $\approx 2\%$ of the density of the solid target material. The density of the material at the bottom of the bowl is ≈ 10 times solid density, which is about the value expected from a strong shock. Thus, there is a rapid 1000-fold expansion (from 10 times solid to 2% of solid density) across the cavity followed by a much slower expansion outside the entrance.

These results vary only slowly with gas dynamic parameters, impactor material, and geometry. Of particular importance is the result that the energy loss out of the hole is not large, so that the observable phenomena can be treated as a small loss to first order accuracy. It should be noted that impact experiments under consideration do not fully satisfy the conditions for this solution, as the areal density of projectiles is only about $10 \text{ kg}/(30 \text{ cm})^2 \approx 100 \text{ kg/m}^2$. They should decelerate in a like amount of target matter of density $\approx 1,000 \text{ kg/m}^3$, i.e., in about 10 cm. Thus, the exit area should be wider than the depth of the hole, and the expansion should be more one dimensional. This is expected to make only numerical alterations to the two dimensional solutions used below.

Hydrodynamic model. The similarity solutions for the flow from the entrance hole can be solved for the opacity and temperature of the exterior flow field. The hydrodynamic equations for the initial one-dimensional unloading wave are

$$x/t = u - c, \quad (1)$$

$$u + \int dp/\rho c = \text{Constant} \quad (2)$$

which can be solved for the isentropic expansion after shock heating for⁵

$$dx/dT = -Fct/T, \quad (3)$$

where γ is the ratio of specific heats, which is ≈ 1.2 in this temperature region, so that

$$F = (\gamma + 1)/2(\gamma - 1), \quad (4)$$

is roughly constant. Equation (3) can be solved for

$$T(x) = T_0 e^{-x/Fct}, \quad (5)$$

which is shown in Fig. 1 for $c = 10$ km/s and $T_0 = 1$ ev for $t = 1, 10$, and 100 microseconds. At 1 microsecond the temperature falls below 0.001 ev by 40 cm due to the rapid initial expansion. At 10 microseconds the temperature drops by about a factor of 3 by 30 cm. At 100 microseconds the temperature only drops 15% by 90 cm—although that distance far exceeds the maximum for which the one dimensional solution is valid for a 30 cm diameter projectile. For the isentropic expansion, the density is related to the temperature through $TdS = 0 = de + pdV$ or

$$\rho = \rho_0(T/T_0)^{1/(\gamma-1)} = \rho_0(e^{-x/Fct})^{1/(\gamma-1)} = \rho_0 e^{-x/ct}, \quad (6)$$

so that density decays somewhat more rapidly than temperature. With them, it is possible to determine the opacity of the plasma.

Optical thickness. The optical thickness to a radiating layer at distance x is

$$\tau(x) = \int_0^x dx' K(x'), \quad (7)$$

where $K(x)$ is the frequency averaged absorption coefficient at x . In the rarefaction flow field, the temperature T is uniquely related to x , so Eq. (1) can also be written as

$$\tau(T_{br}) = - \int_0^{T_{br}} dT K(T) dx/dT = 1, \quad (8)$$

where by the definition above, the optical thickness $\tau(T_{br})$ at T_{br} is unity, since the optical thickness unity surface is where the radiation originates. Using dx/dT from Eq. (3) makes it possible to evaluate T_{br} as a function of x as well. If the primary absorption mechanism is photoelectric absorption by highly excited atoms and bremsstrahlung on ions, the absorption coefficient is of the Kramers Unsold form⁶

$$K = ANe^{-E/kT}/T^2, \quad (9)$$

where N is the density, E is the effective ionization energy, and $A \approx 3 \times 10^{-17} \text{ cm}^2\text{-ev}^2$ is a constant that depends inversely on the cube of photon frequency. For weakly ionized plasmas with Saha ionization, absorption is by bremsstrahlung, which gives a slightly different form, but their dominant temperature dependence is through the exponential, so the two equations give similar absorptions to within the approximations implicit in either.

Substituting Eqs. (5) and (6) into Eq. (8) gives Fig. 2, which shows T and the integrated optical thickness as a function of distance from the impact surface at a time of $t = 10$ microseconds after impact. The temperature falls from $T_0 = 1$ ev to about 0.45 ev by 45 cm while the opacity falls from about 100 to 0.01 . The surface of unit optical thickness is about 25 cm from the surface, where the temperature is about 0.63 ev. The two curves intersect at such a large angle that even doubling the temperature would only shift the intersection to about 23 cm.

Time dependence. Figure 3 shows the intersections at 10 and 30 microseconds. The former is that shown on Fig. 2, but with a doubled scale. The latter is three times later. Its unit opacity surface is at about 80 cm, so it has moved out about a factor of 3 further in distance. However, the temperature there is still about 0.6 ev, which is consistent with the demonstration in the previous note that the brightness temperature falls only logarithmically with time. At

later time the one dimensional solution continues to exhibit this same scaling: the radiating surface moves further from the impact surface, but the temperature remains about the same. However, at times longer than about 30 microseconds, the material extends well beyond the dimension of the impact area, so the one dimensional solution no longer strictly applies.

Impact area. As noted above, the one-dimensional solution no longer holds for distances from the surface larger than the diameter of the impactor, as the flow becomes two dimensional there. The correction to the density is geometric; it falls as $1/[1 + (x/D)^2]$. There is also a correction to the internal energy and temperature. When the rarefaction fans reach a given radius, the flow is turned, which requires much of the remaining energy. This effect can be modeled by applying the geometric reduction to the temperature as well. Figure 4 shows the resulting temperature and opacities at 100 microseconds as functions of distance x for $D = 30$ and 100 cm.

For 30 cm, the optical thickness drops to unity at about 20 cm, where the temperature is about 0.65 ev. For 100 cm, the optical thickness drops to unity at about 60 cm, where the temperature is again about 0.65 ev. The optical thickness drops to unity at about $2/3 D$. These profiles are essentially steady state; there is little variation for times $> D/c$. While the optical thickness is still several hundred for small x , it falls more rapidly for finite D than for the very large D cases treated above. That produces a smaller radiating region but exposes a somewhat higher temperature unit optical thickness, and hence a higher brightness temperature.

Surface temperature is not observed directly; it is seen through an opaque plasma. Figure 5 shows the temperatures and opacities at 100 microseconds for $D = 30$ cm for surface temperatures of $T_0 = 1$ and 2 ev. The peak opacities are 2,000 and 200, respectively. For $T_0 = 2$ ev, the optical thickness falls to unity at 30 cm, where the temperature is about 0.8 ev. For $T_0 = 1$ ev, it falls to unity at 20 cm, where $T \approx 0.65$ ev. The change in the distance to the radiating surface is small, although the radiated power is greater by a factor of $(0.8/0.65)^4(35/25)^2 \approx 2.3 \times 2 \approx 4.6$, which should be observable. Of the two factors, the second, geometric term, which is model dependent, contributes about half the uncertainty. The first, which reflects the optical thickness (also model dependent), suppresses the effect of a factor of 2 variation in surface temperature into a $0.8/0.65 = 1.23$ variation in brightness temperature.

Small objects present quite different opacity profiles. Figure 6 shows the temperatures and opacities at 0.1 and 1 microseconds for a $D = 1$ cm projectile for $T_0 = 1$ ev. For $t = 0.1$ microsecond, the optical thickness is less than unity at all distances, so radiation is from the surface and $T = T_0 = 1$ ev. For $t = 1$ microsecond, the maximum optical thickness is only about 2, so radiation is still from close to the surface, and $T \approx T_0$. Thus, for small projectiles of the size used in laboratory experiments, the optical depth of the plasma is small, in contrast to very large depths of the larger impactors treated above. Such optically thin plasmas have little radiation

content, so the transport of energy by radiation is further suppressed, manifesting itself in the appearance of strong spectral lines.

Summary and conclusions. This note uses scaling results derived earlier for the growth, size, and temperature produced by impacts to discuss the radial temperatures profiles they produce. While the plasmas cool in milliseconds, they offer unique information about the thermodynamic state and material properties of the target material. The brightness temperature can be estimated from known two-dimensional similarity solutions. Regions close to unit optical thickness contribute effectively to the radiation, hence, they determine the plasma brightness temperature. The estimates of temperature as a function of time can be combined with the estimates of the exit hole size to estimate the total observable signal, which should be readily observable from distances of hundreds of kilometers.

The specific energy of the plasma produced by impact is determined by the velocity of the impactor; for impact velocities on the order of 10 km/s, this gives initial temperatures on the order of 1-2 ev. While similarity solutions are available for the subsequent flow, they are complicated by the irregular geometry of the impactor and target, unknown shape and composition of the target, unknown equation of state, and preexisting fractures in the target. These similarity solutions determine the temperature and density profiles of the blow off plasma, and hence the local and integral absorption to a surface in the plasma. The radiation comes from the surface with unit optical thickness to the void, whose temperature is the brightness temperature. As time since impact increases, that surface moves further from the target and its temperature falls slowly.

The flow diverges after it reaches a distance from the body roughly equal to the impactors diameter. Thereafter, the density and temperature fall more rapidly than the solutions for the original one dimensional expansion, which fixes the unit optical depth surface at a distance about $2/3 D$ from the target, fixing the temperature profile and exposing a slightly higher brightness temperature than would be visible through the thicker 1-d plume. Sensitivity to the surface temperature is strongly reduced by thick plumes. However, for very small impactors the plumes are thin, and it is possible to observe the surface temperature directly.

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T vs X; t

Fig. 1. Temperature versus distance at various times (microseconds).

Fig. 2. Temperature and optical thickness at 10 micoseconds for $T_0 = 1$ ev.

T & sum Kdx vs x; 1 ev

Fig. 3. Temperatures and optical depths at 10 and 30 microseconds.

Fig. 4. Temperatures and optical thicknesses at 100 microseconds for 30 and 100 cm diameters.

T & Kdx vs x; $T_0 = 18.2$ ev

Fig. 5. Temperature and optical thickness at 100 microsecond for $T_0 = 1$ & 2 ev.

T & Kdx vs x; small obj

Fig. 6. Temperature and optical depths for 1 cm projectile at 0.1 and 1 microsecond.