INVESTIGATIONS OF THE LUMINOUS ENERGY AND LUMINOUS EFFICIENCY OF EXPERIMENTAL IMPACTS INTO PARTICULATE TARGETS. C. M. Ernst and P. H. Schultz, Brown University, Department of Geological Sciences, Box 1846, Providence, RI 02912 (Carolyn_Ernst@brown.edu).

Introduction: A portion of a projectile's initial kinetic energy is partitioned into heat on impact, resulting in thermal heating and, in some cases, vaporization of projectile and target materials. If the impact is sufficiently energetic, the heated materials will radiate light in the visible wavelength range. The fraction of initial kinetic energy converted into luminous energy is the luminous efficiency.

Numerical simulations have considered the luminous efficiency of impacts in the visible wavelength range [1,2], however the results span many orders of magnitude (10^{-6}-10^{-1}) and consider only the evolving vapor phases. Estimates also have been based on laboratory experiments (10^{-6}-10^{-4}) [3-5] and natural observations (~10^{-3}) [6]. The former studies address only impacts into solid targets, and the latter relies on uncertain projectile size estimates. The present study calculates the luminous energy and luminous efficiency of experimental impacts into particulate targets. The results have implications for planetary impact observations that currently rely on theoretical and non-particulate target luminous efficiency estimates.

Background: There are two main sources of impact-generated radiation: emission lines from vapor (atomic and molecular) and thermal blackbody emissions from heated melt, particulates, and vapor condensates (if present). For impacts into solid targets, principally the vapor emissions are observed, thereby resulting in a very short-duration intensity signal (~10-20μs) [3,4]. In order to analyze impacts of different velocities and diameters on comparable timescales, the time can be normalized with respect to the penetration timescale (the time it takes the projectile to travel the length of its diameter into the target along its trajectory):

$$\tau = \frac{t}{(a/v)} \qquad (1)$$

where t is time, v is the impact velocity, and a is the projectile diameter. Using this normalization for typical macroscopic experimental impacts, times of 10-20μs correspond to τ ~ 10-20.

Light intensity evolution for impacts into nonvolatile particulate targets has been observed experimentally [7-9] and is noticeably different from that of solid target impacts. In the particulate case, a thermal blackbody signal is observable for a prolonged period of time as the heated melt and particulates continue to radiate ($t > 2$ms; $\tau > 2200$).

Depending on target type and initial kinetic energy, the earliest stages of the light evolution may be complicated by the presence of vapor. Impact experiments using carbonates reveal that the vapor does not produce a thermal signal and its emissions are extremely short lived (lasting τ = 10-20 in preliminary laboratory experiments). In these experiments, vapor did not affect the observation of later-time blackbody cooling phenomena because no condensates formed. For silicate powders, a significant amount of luminous energy is emitted at late times ($\tau > 200$). This additional light output enhances the total emitted luminous energy (and luminous efficiency).

Experiments: Experiments were performed at the NASA Ames Vertical Gun Range. Two high-speed photodiode systems (previously described in [7]) recorded time-resolved intensity measurements over narrow wavelength ranges. Pyrex spheres (4.18mm diameter) impacted pumice dust targets at angles of 30º and 90º (measured from the horizontal). Velocities ranged from 5.2-5.5km/s. The experiments were performed in near-vacuum conditions (< 0.5Torr).

Analysis: Ratios of the wavelength-filtered intensity curves established color-temperature evolution through time, assuming a blackbody-radiating light source. The effective emitting source area was calculated from the observed intensity and temperature. For a purely kinetic event, the integrated luminous energy (LE) of an impact can be determined by:

$$LE = \sigma \int_0^t T^4 A_s dt \qquad (2)$$

where T is the color temperature, A_s is the effective source area, and σ is the Stephan-Boltzman constant. For these experiments, the luminous energy was integrated over two time periods (τ = 0-200 and τ = 0-1000).

Results: The luminous energy for visible wavelengths (0.34-1.0μm) was calculated for 30º and 90º impacts at similar velocities. These results are displayed as cumulative energy over time in Figure 1. The peak intensity for the 30º and 90º impacts occurs at τ ~ 16 and τ ~ 31, respectively, and decays to half of its peak value by τ ~ 107 and τ ~ 222. As much as 50-60% of the visible luminous energy is emitted after this time. Such late-time contributions significantly increase the total luminous efficiency.

The luminous energy for infrared wavelengths (1.0-4.8μm) also was calculated. Since these experiments involved color temperatures ranging from 3000-4500K, more energy is released in the infrared range. Less energetic impacts are therefore easier to detect in the infrared (rather than visible) range. A comparison of the visible and infrared luminous energy outputs for the 30º and 90º impacts is also illustrated in Figure 1.

The luminous energy over a given wavelength range (LE_λ) is assumed to be a simple fraction of the total kinetic energy:

$$LE_\lambda = \eta_\lambda KE \,. \qquad (3)$$

This fraction (η_λ) is the luminous efficiency. For the current experiments, η_λ values were calculated for both the visible and infrared wavelength ranges. Luminous efficiency values for both integration times are listed for

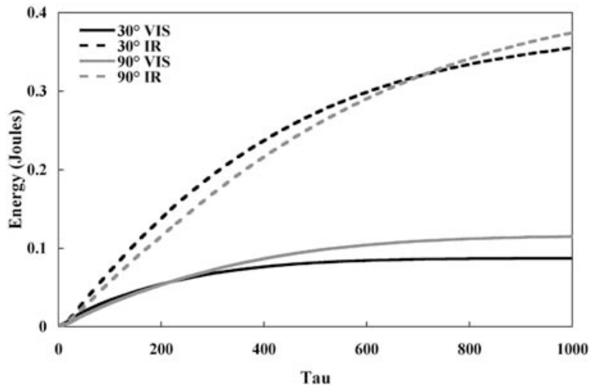

Figure 1. Observed cumulative luminous energy in the visible (0.34-1.0μm) and infrared (1.0-4.8μm) wavelength ranges for experimental hypervelocity impacts into pumice dust targets at 90º and 30º. Luminous energy is calculated from the observed blackbody temperature and source area through normalized time (τ).

the 30º and 90º impacts in Table 1. For the long integration time, η_{VIS} is on the order of $5x10^{-5}$ for both impact angles. This observed value falls within both the theoretical and the experimentally observed ranges. For a given set of initial conditions, a 30º impact has higher peak intensity than a 90º impact [7,8], but vertical impacts exhibit higher temperatures after the intensity peak [7] and therefore have higher total luminous energy outputs. These factors combine to result in similar luminous efficiency values. In both cases, the luminous efficiency in the infrared range is greater than that in the visible wavelength range (see Table 1).

τ	λ range	η_λ (90º)	η_λ (30º)
0-200	VIS	$2x10^{-5}$	$3x10^{-5}$
0-1000	VIS	$5x10^{-5}$	$4x10^{-5}$
0-200	IR	$5x10^{-5}$	$7x10^{-5}$
0-1000	IR	$2x10^{-4}$	$2x10^{-4}$

Table 1. Luminous efficiency values for visible and infrared wavelengths over τ = 0-200 and τ = 0-1000.

Implications: Luminous efficiency is a useful tool for observing impacts. For example, luminous efficiency values can be used to calculate projectile size for observed lunar impacts or to predict the light output for planned or predicted impact events. Although initial impact parameters can affect the luminous efficiency, experimental impacts into particulate targets provide an important basis of comparison for impacts into planetary surfaces, particularly with respect to the later stages affected by incandescent ejecta.

Lunar impacts. Size estimates of objects that impact the Moon are based on the observed light output [6]. These estimates are calculated using an assumed value for the luminous efficiency. Orders of magnitude variation in this assumed value can drastically affect the resulting size estimates. This is especially relevant for estimates of the size flux of Leonid meteors.

Observations of lunar Leonid impacts were made in 1999 and 2001 [10-14]. Four of these observations were published as time-resolved intensity data [12,14] and displayed surprisingly long-duration decay signals. Based on laboratory experiments, the long duration for the Leonid impacts can be attributed to the effects of large quantities of incandescent ejecta, rather than just the short-duration vapor plume. The laboratory observations demonstrate the importance of observing the entire duration of the impact-generated light when estimating the luminous efficiency.

Deep Impact. Results from laboratory experiments also can be used to make first order predictions of the luminous output of the upcoming Deep Impact (DI) mission. Two extrapolations have been made using assumptions about how the temperature scales from laboratory to planetary dimensions: Case 1 - the temperature scales as $T \sim v^{0.75}$ [8]; Case 2 - the temperature remains the same both for DI and the laboratory. In Case 1, the total visible luminous energy out to τ = 1000 (t = 90ms) is ~ 6MJ for the 90º case, which corresponds to a luminous efficiency of $\sim 3x10^{-5}$. In Case 2, the total visible luminous energy is ~0.4MJ, corresponding to a luminous efficiency of $\sim 2x10^{-5}$. These calculations are based on particulate, nonvolatile targets.

If the upper layers of Comet 9P/Temple 1 consist of a loosely bonded lag of refractory particulates, then such extrapolations provide valuable estimates. The actual light output will be greatly affected by additional factors such as target porosity, volatile content, strength, and optical depth. Also, luminous efficiency is expected to increase with velocity [1]. If the forming crater does not obscure the radiation, the DI collision could produce significantly more radiant energy than estimated here.

Conclusions: Light emitted by experimental impacts into nonvolatile particulate targets can last well beyond τ = 1000, far longer than impacts into solid targets. The luminous efficiency of these impacts is affected by the long duration of the thermal signal, with as much as 60% of the visible-wavelength luminous energy being emitted after the intensity peak. Observed visible luminous efficiency values of $\sim 5x10^{-5}$ fall within the estimated theoretical and experimentally-observed ranges. Based on these measurements, first-order predictions of the Deep Impact luminous output are between 0.3-6 MJ and the signal should last for many frames of the Medium Resolution Imaging camera. The actual luminous output will depend on the properties of the comet surface.

References: [1] Nemtchinov, I. V. et al. (1998) *Solar Syst. Res.*, *32*, 99-114. [2] Shuvalov, V. V. et al. (1999) *LPS XXX*, #1045. [3] MacCormack, R. W. (1963) *Proc. 6th HVIS*, *2*, 613-625. [4] Eichhorn, G. (1975) *Planet. Space Sci.*, *23*, 1519-1525. [5] Kadono, T. and A. Fujiwara (1996) *JGR*, *101*, E11, 26,097-26,109. [6] Bellot Rubio, L. R. et al. (2000) *AsJ*, *542*, L65-L68. [7] Ernst, C. M. and P. H. Schultz (2004) *LPS XXXV*, #1721. [8] Ernst, C. M. and P. H. Schultz (2002) *LPS XXXIII*, #1782. [9] Ernst, C. M. and P. H. Schultz (2004) *LPS XXXIV*, #2020. [10] Dunham, D. W. et al. (2000) *LPS XXXI*, #1547. [11] Bellot Rubio, L. R. et al. (2000) *Earth, Moon, Planet. 82-83*, 575-598. [12] Ortiz, J. L. et al. (2002) *AsJ*, 576, 567-573. [13] Cudnik, B. M. et al. (2002) *LPS XXXIII*, #1329. [14] Yanagisawa, M. and N. Kisaichi (2002) *Icarus*, *159*, 31-38.