Observations of the lunar impact plume from the LCROSS event

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Received 17 September 2010; revised 14 October 2010; accepted 19 October 2010; published 4 December 2010.

[1] We observed emission from sodium (Na) ejected from the Lunar Crater Observing and Sensing Satellite (LCROSS) impact into Cabeus Crater on October 9, 2009, using the McMath-Pierce telescope. In our 88 km^2 field of view, we saw on the order of 2 g of Na in the first 9 minutes after the LCROSS impact. A comparison of our observed Na above the limb with simulations that assume a gas temperature of 1000 K indicates that 0.5 − 2.6 (1.5 ± 1) kg of Na were released during the LCROSS impact. Lower temperatures would result in a lower total sodium release. The model of an isotropic expanding cloud best reproduces the observations. **Citation:** Killen, R. M., A. E. Potter, D. M. Hurley, C. Plymate, and S. Naidu (2010), Observations of the lunar impact plume from the LCROSS event, *Geophys. Res. Lett.*, *37*, L23201, doi:10.1029/2010GL045508.

1. Introduction

[2] On October 9, 2009, 11:31:19 UT, the Lunar Crater Observing and Sensing Satellite (LCROSS) impacted the Moon in attempt to reveal whether water ice is condensed in the permanently shadowed regions near the lunar poles. The impact of the 2350 kg Centaur upper stage at 2.5 km/s onto the floor of Cabeus crater was intended to loft material from the crater floor into sunlight [*Colaprete and LCROSS Team*, 2009]. A small shepherding spacecraft weighing 610 kg followed, making spectroscopic measurements of the Centaur impact plume, and itself impacting at 11:35:35.05 UT.

[3] Recent reports indicate that water was detected in the impact plume [*Colaprete et al.*, 2010]. We present the observations of Na released by the LCROSS impact into Cabeus for future comparison with observations of other volatiles, which would elucidate the physical conditions of the impact and/or the source of polar volatiles.

2. Observations

[4] We used the McMath-Pierce main telescope with the long slit on the stellar spectrograph to observe Na and water emission, along with the McMath-Pierce East Auxiliary telescope to image the impact plume in orthogonal polarizations. We did not observe a significant polarization difference after impact, implying that less than 5% of the reflected light was scattered from the impact cloud. We can place an upper limit on water in our field of view of 0.1 g cm^{-2} based on the RMS noise level in the water bands in the spectral range of the observations. In contrast to our non-detections of water and dust, we detected Na throughout the first 9 minutes after the LCROSS impact.

[5] Na was observed with a 160 micron (wide) slit subtending an angular size of 100 × 0.237 arcseconds (″). The plate scale was 1.93 km/″, giving a field of view at the moon of 193 km by 0.4574 km. On Oct. 9, 2009, the seeing was 2″ FWHM at Kitt Peak and there were no clouds. To save readout time we binned two adjacent pixels, giving an effective resolution of 2″ or 3.86 km given the plate scale. The observation numbers, times and positions of the slit are given in Table 1. At the time of impact we placed the slit over the impact point in Cabeus crater, 84.68°S, 48.72°W. Observation 39, a 90 second (s) exposure, was begun at the impact time (Table 1). An image of the slit was taken by a camera positioned above the entrance slit (Figure 1). Observation 40, a 120 s exposure, was also positioned on Cabeus crater, post impact. Observation 41 and subsequent observations were taken off the limb of the Moon south of the impact site with the slit length tangent to the limb as close to the limb as possible. Note that observation 41 occurred after the shepherding spacecraft impacted.

[6] We obtained flats, Th-Ar lamp comparisons, sky exposures, and equatorial Moon exposures for calibration. Na emission was extracted by standard methods: subtracting dark counts and sky background from the spectra and, finally, subtracting the continuum from under the emission feature. Calibration was obtained by comparing counts in the continuum to the known reflectance given by a Hapke model of the lunar surface at the point where the continuum was obtained near the equatorial limb at approximately 297° longitude in mare [*Helfenstein and Veverka*, 1987]. We saw no Na above the polar limb prior to the impact consistent with the previously observed morphology [e.g., *Potter and Morgan*, 1998]. The emission seen at the impact site during exposures 39–40 and the emission seen tangent to the limb just south of Cabeus crater (exposures 41–42) were converted to line of sight column abundance shown in Figures 2 (left) and 2 (right), respectively, assuming optically thin emission and using a g_value (emission per atom per second) for D_2 of 0.53 photons atom^{-1} s^{-1} [*Chamberlain and Hunten*, 1987].

[7] The impact flash was observed both in the CCD images with the East Auxiliary telescope and with the stellar spectrograph observing the Na D_2 emission (Figure 2). Na emission was observed until 9 minutes after impact. The Na emission seen during the first 90 seconds after impact are bright but confined to an area with full width at half maximum (FWHM) of 40 km. The maximum emission seen over Cabeus crater was 150 ± 25 kiloRayleighs (kR) during observations 39. Integrating the Gaussian fit along the slit, we obtain a total mass of 1.5 – 1.8 g of Na in the field of view during integration 39. The FWHM is difficult to estimate for

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0094-8276/10/2010GL045508

Table 1. Observation Position, Start Times and Duration for Selected Sodium Observations

Observation Number	Position	Start Time (UT)	Duration (sec)	Mass in Slit (gm)
38	Cabeus Crater before impact	11:28:28	90	
39	Cabeus Crater at impact	11:31:19	90	1.5
40	Cabeus crater post-impact	11:33:13	120	—
41	off limb	11:35:45	120	2.3
42	off limb	11:38:12	120	0.7
43	off limb	11:40:39	120	

integration 40 because the signal to noise was too small in the wings of this observation looking into the crater.

[8] The peak column abundance seen above the limb during integration 41 was 0.8×10^{11} cm^{-2}, with an e-folding sigma of the Gaussian fit along the slit of 100 km. We integrated along the slit and averaged, giving an average column abundance in our slit between 4.5–6.5 minutes post-impact of 6.5×10^{10} atoms cm^{-2}. This amounts to 2.2 g of Na in the field of view for integration 41. During integration 42, we fit the observations with a peak column of 0.28×10^{11} cm^{-2} with a sigma of 83 km. The average column abundance during integration 42 was 1.8×10^{10} atoms cm^{-2}. Then, the mass of Na in the field of view of the telescope during integration 42 was 0.6 g.

[9] The total field of view of the stellar spectrograph was only 88 km^2, but structure observed in the length of the slit is indicative of the overall size of the Na plume. If we assume a hemispherical plume of approximately 100 km radius, we can estimate the area that the plume subtends on the sky as 1.6×10^4 km^2. Thus, the slit only sees about 0.55% of the entire plume. We can expect that the total amount of Na released by the impact to be 2–3 orders of magnitude higher than what appeared in the slit, given the small fraction of the plume that the slit covered. In order to extrapolate what we observed to the total amount of Na released by the impact, we compare all observations to models.

3. Simulations and Results

[10] We ran a Monte Carlo model [*Crider and Vondrak*, 2000] of the Na plume for a wide variety of initial conditions to cover the expected physical characteristics of the impact plume. For each assumed initial temperature, ranging from 200 to 2500 K in 50 K increments, we executed a set of model runs where we constrained the angular distribution of the vapor plume material at release to each of three different physical scenarios: isotropic; high angle; and upside-down lampshade. In the isotropic case, the initial direction of the particles is distributed evenly among the 2π upward hemisphere from the impact point. Typical impact ejecta are released in a cone at about 45° from the local vertical, forming a structure that resembles an upside-down lampshade [*Melosh*, 1989] simulated by distributing the initial velocity direction around 45° with a 15° FWHM in the angle. This represents gas that is entrained in the solid ejecta. In the high angle case, the initial direction of the particles is concentrated near the local vertical and falls off rapidly towards the horizontal with very few particles emitted within 45° of the horizontal. This "high angle" pattern is observed in hollow impactors onto porous materials [*Schultz et al.*, 2010]. In each case, the magnitude of velocity is taken from a Maxwellian distribution at the assumed initial temperature. The atoms are tracked on ballistic trajectories under the influence of lunar gravity. Very few of the atoms return to the surface in the short time span of the observations.

[11] The resulting Na plumes for each of the three emission angle scenarios are shown in Figure 3 for the 1000 K release temperature. The model tracks the Na atoms as a function of time, and output is binned according to the timing of the observations and projected into the plane defined by the field of view from Earth. In Figure 3, the impact point is at x = 0 and y = −1722, marked by a '+' in Figure 3 (top right). More negative values of y roughly correspond to higher altitude. Figure 3 shows the modeled column density for observations 39 (Figure 3, top) through 42 (Figure 3, bottom). The slit, shown as the dashed line, is oriented mostly in a horizontal alignment with respect to the local vertical at the impact site, and covers a small vertical extent of the plume. Each of a million model particles is weighted to 2.60×10^{19} real particles/simulation particle to represent the total release of 1 kg of Na. In order to compare the models with observations we smeared the models to the same resolution as the observations, although the model output is shown in higher resolution in Figure 3.

[12] The initial direction of the velocity for the particles controls the distribution of particles from that time forward in this collisionless regime. The model output indicates that the column density varies as a function of position in the plume, and that the initial release properties are important in the morphology of the plume. Although the data appear to show that the plume is drifting toward the terminator at approximately 0.1 km/s, this motion is not included in the model. In the isotropic release (Figure 3, left), the plume is much broader than in the other two cases. In the 45° angle ejecta-curtain release scenario (Figure 3, middle), the model predicts that 2 peaks would exist in the observations along the slit in integrations 41 and 42. Two peaks were not observed (see Figure 2b), suggesting that this curtain component was not the dominant distribution of the ejected Na. In the high angle plume release scenario (Figure 3, right), for the same amount of Na released as in the isotropic case the model predicts higher column density at the peak because the high angle plume material is confined to a smaller spatial region.

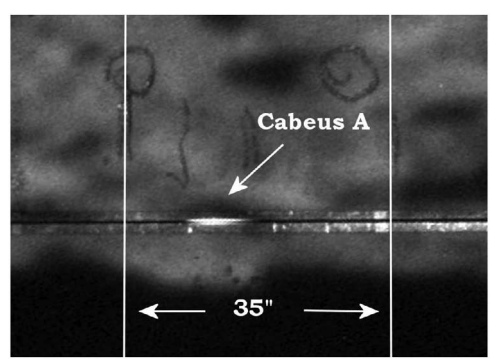

Figure 1. A camera mounted above the slit captured this picture of the slit with the image of the moon on the top of the spectrograph tank during the first observation after the impact (observation 39). Subsequent to image 40, we moved the slit just off the limb, maintaining the same orientation. Hand-drawn marks were a guide for the observers.

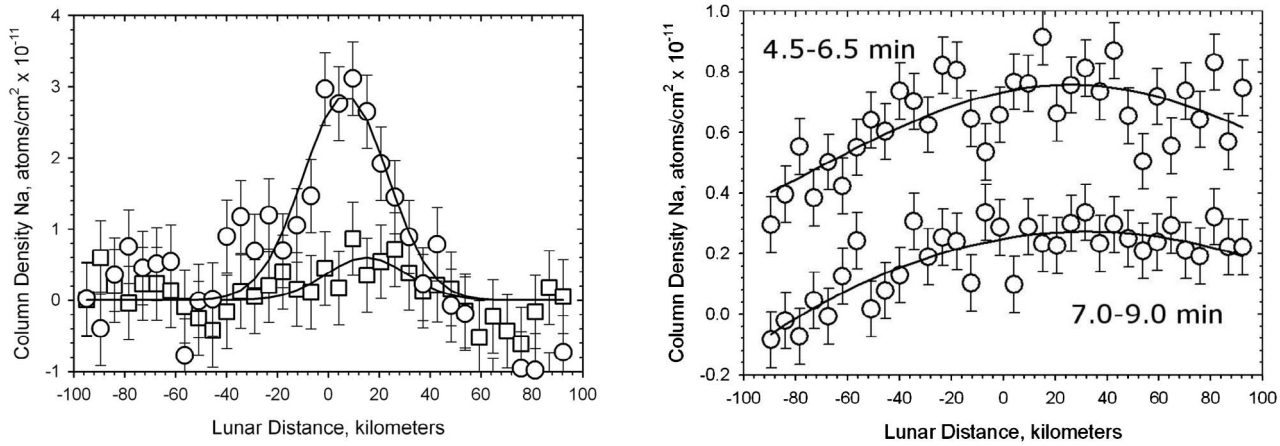

Figure 2. Na column abundance (in units of 10^{11} atoms cm^{-2} along the line of sight) computed using (left) observations 39 at impact to 90 seconds after impact (open circles) and 40 at 90 – 210 seconds after impact (squares) over Cabeus crater, and (right) 41 and 42, off the limb south of Cabeus crater. The emission probability (g_value) for Na D_2 is 0.53 (photons s^{-1} atom^{-1}). Distance is measured along the slit from the center of the impact in km at the moon.

[13] The slit position shifted for integration 41 and 42 into a higher altitude portion of the plume than during integrations 39 and 40. Note that the observed column density is similar for integration 40 (within the crater) and integration 41 (later in time and at higher altitude). The model results suggest that this is because the plume is expanding up in altitude with time. The greatest column density in the model is at altitudes above the slit placement for both of these observations. The slit was not looking through the densest part of the vapor cloud, according to the model.

[14] Next we extrapolate the observed Na in the slit to the total Na released by scaling the model column density to

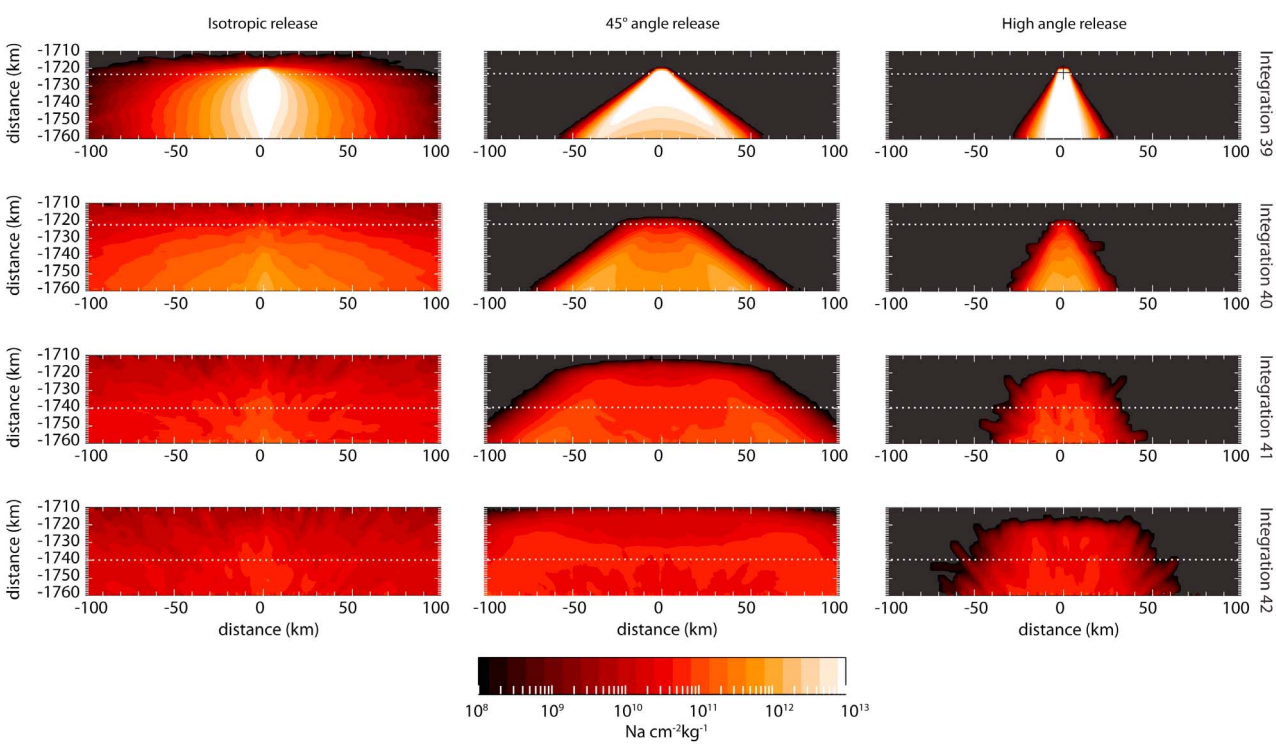

Figure 3. The column density of Na in the plane perpendicular to the line of sight is shown for three modeled release scenarios: (left) isotropic release; (middle) 45° angle curtain; and (right) high angle plume. The successive images give the integrated values corresponding to the time periods of the McMath-Pierce observations (top) 39 to (bottom) 42. The position of the slit is shown by the dotted line. Note that the slit moves from within the crater (y = −1722 km) in the first and second rows to above the limb (y = −1740 km) in the third and fourth rows. The model results show the line of sight column density per kg of Na released at 1000°K.

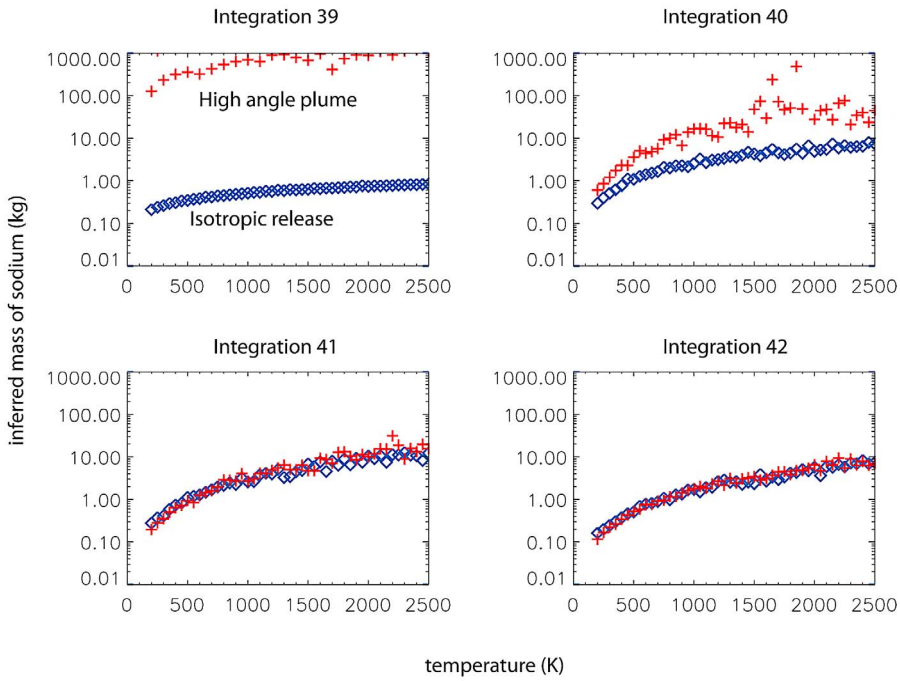

Figure 4. These figures show the inferred total mass of Na released as a function of the release temperature by relating the peak observed column density to the modeled column density. For each observation, 39–42, the isotropic distribution model (diamonds) predicts a lower mass for the same observed column than the high angle plume model (pluses).

match the observed number of atoms along the line of sight of the spectrograph slit at a given time. If the model accurately represents the gas release, then the conversion of the observed columns to the total integrated mass would be the same for each of the 4 observation periods, even though they are from different times and locations. To do this analysis, we rebin the model output into the same spatial resolution as the observations and convolve the model output with seeing and noise. Then, we compare the width of the feature, the peak column density, and the slit-integrated total abundance of the model to the observations for each temperature and angular release case. We found that the best diagnostic that is available to convert the observations into total vapor released is to compare the peak column density in the data to the model. In Figure 4, we show the inferred total mass of Na released as a function of the assumed initial temperature for the isotropic model (blue diamonds) and the high angle plume (red crosses.) For the same observed Na column, a lower initial temperature translates into a lower inferred total ejected mass of Na vapor than that from a higher initial temperature. If the initial temperature had been 200 K, only a few tenths of a kg of Na were released, compared with several kg for a 2000 K release temperature. This is because the gas plume expands more rapidly if it is released with a higher temperature. Thus the model column density near the impact point is higher at the times shown here for a low temperature release than a high temperature release.

[15] Isotropic release provides a more consistent inferred mass for observations 40–42, at all temperatures (Figure 4). In contrast, the high angle plume, where the inferred initial mass decreases for each subsequent integration regardless of the assumed temperature, does not reproduce the time evolution of the data. For isotropic release, integration 39 gives lower inferred initial mass than the other three observations. However, the model/data comparison assumes that all of the material in the model is illuminated, and thus, is visible to the telescope if it is in the telescope's field of view. At low altitude, topography can cast shadows on the gas, obscuring it from view. As the gas cloud produced by the impact expands, the fraction of the gas at low altitude, shadowed by topography, decreases. Thus the error introduced by this effect is greatest for observation 39 for which the total mass release inferred from the isotropic model is lowest. In contrast, the high angle plume model would require, unrealistically, that less mass is visible in later times. The data therefore suggest that the Na release from the LCROSS impact is not distributed like the high angle solid ejecta.

[16] Separate analyses have indicated that the initial temperature of the impact was around 1000 K [*Gladstone et al.*, 2010; *Hayne et al.*, 2010], as modeled in Figure 3. Although the surface temperature measured by the DIVINER instrument decreased to 600 K 90 seconds after impact, only the release temperature is important for the dynamics of the sodium gas. The sodium was only observable during the first ten minutes after impact. In each of the 4 observation periods, the isotropic release at 1000 K model scales to 0.5–2.6 kg of Na released. Using the integrated column along the slit gives similar answers (0.4–4.1 kg), but we use the peak density because the uncertainty at the wings of plume affects the answer if we use the density integrated along the slit.

4. Conclusions

[17] The amount of Na observed within the slit field of view the McMath solar telescope is on the order of 2 g (Table 1). The fractional area of the field of view of the slit to the entire vapor plume based on the observed horizontal scale of the plume was about 0.5%. Thus, the total amount

of Na released by the LCROSS impact was 2–3 orders of magnitude greater. Modeling of the plume to accompany the data analysis assuming a gas temperature of 1000 K suggests that 0.5 – 2.6 (1.5 kg ± 1) kg of Na were released by LCROSS. Figure 4 shows how the inferred total mass of Na released by the impact can be scaled by the assumed temperature of the gas at release. We find that the isotropic release mechanism better represents these data than the high angle plume. Future comparisons with the LCROSS following spacecraft might reveal more about the plume morphology.

[18] Further analysis is required to determine the origin of the Na and water at the lunar poles. However, we know that the Na exosphere is peaked at the subsolar point on the moon, and is for the most part gravitationally bound. Therefore preferential loss of Na in equatorial regions would imply that Na, and other volatiles, should accumulate at higher latitudes over time. Since the lunar Na composition is 0.004 [*Heiken et al.*, 1991], a release of 1.5 kg of Na would correspond to 375 kg of lunar material if the Na were released in proportion to its lunar abundance. That mass is several orders of magnitude lower than the expected mass of material ejected by this impact. This would imply that either the Na was incompletely degassed from the regolith in this event or was instead degassed from a Na/ice mix. This is not surprising, considering the relatively low vapor pressure of silicate rocks at 1000 K [*Walter and Carron*, 1964].

[19] **Acknowledgments.** This research was supported by NASA under a grant to the DREAM Team of the NASA Lunar Science Institute. Observations were obtained at the McMath Pierce Solar Telescope on Kitt Peak, Arizona, operated by the National Solar Observatory under agreement with the National Science Foundation.

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