EMISSION SPECTRA OF SHOCK COMPRESSED SOLIDS

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New optical wavelength emission spectra recorded during dynamic compression of MgO shocked to 55-65 GPa, and CaAl_{2}Si_{2}O_{8} (glaucoblagyro) shocked to 37-40 GPa, and a control sample of steel shocked to 40 GPa suggest that transparent brittle solids exhibit both thermal and characteristic line spectra. These spectra are related to the state of brittle materials shocked to successively higher pressures and temperatures. These regimes of emission spectrum behavior are proposed to occur in transparent solids upon shock compression: (1) the characteristic line spectrum regime such as observed in MgO and previously in SiO_{2}, CaAl_{2}Si_{2}O_{8}, and NaCl, (2) the heterogeneous hot spot (previously) radiation regime observed in CaAl_{2}Si_{2}O_{8} (glass) and previously in all solids undergoing shock-induced phase transformations, and (3) the blackbody emission regime observed in the high pressure phase regime of MgO, SiO_{2}, CaO, CaAl_{2}Si_{2}O_{8}, and MgSiO_{3}. The onset of regime (3) appears to be useful for estimating shock-induced polymorphism whereas the onset of regime (2), where the sensibility approaches unity, represents achievement of local thermal equilibrium in the shocked solids.

1. INTRODUCTION

Early optical studies of brittle transparent minerals during shock compression were carried out to determine high temperature (\sim 2000K) at relatively high Hugoniot pressures\textsuperscript{1-4}. Recently, experiments on CaAl_{2}Si_{2}O_{8}, SiO_{2}, CaO, CaAl_{2}Si_{2}O_{8}, and CaSiO_{3} at low shock pressures\textsuperscript{5-16} and this study demonstrate that shock information is a complicated process. The data suggests that both brittle failure and shock bonding are important modes of shock deformation at lower stresses and that several factors determine the type of optical emissions observed.

2. EXPERIMENTAL

A brief outline of the equipment and procedure will be given (for a more detailed explanation, see Refs. 7 and 9).

Tungsten flyer plates mounted in Plexiglas plates were launched by a 40mm single-stage gun into a vacuum tank containing the sample mounted upon a copper driver plate (Fig. 1). As the shock wave travels through the sample any scattered light passes through the unshocked portion of the sample to an expandable surface mirror which reflects the light out of the vacuum tank to the recording system. The recording system is triggered by an impact of the projectile and consists of a spectrometer leading to an intensified charge-coupled detector which captures the signal. A scanning electron beam "reads" the detector and sends the digital data to a microcomputer and digitizer memory, where the resulting spectrum from 600 to 850 nm over 500 channels may be

![Fig. 1: Apparatus for observing shock-induced emission spectra of transparent materials. Projectile velocity is determined from interruption of He-Ne laser beams from 400-nm shadow-phones taken at two times. The light from shock-compressed sample passes into the spectrometer and PIN photodiode along the paths indicated. Spectrum dispensed by the spectrometer is detected and accumulated on the silicon target, read out, digitized, and then stored on the memory in DMA console. The detector is electronically open for a preset, 150 to 600 nsec time duration by a gate pulse generator which is initiated by the trigger pin. The gate pulse and the time variation of the shock-induced radiation are recorded by photodiodes (after Kamps and Ahrens, Ref. 7).
stored and displayed. The detector was gated to collect light only while the shock wave front was near the center of the sample to avoid complicating edge and free surface effects. In addition to the above, a broad band flash photolysis collects a portion of the emitted light and provides a record of optical light intensity versus time during an experiment.

Spectral radiation calibration of the detector was accomplished with a standard tungsten ribbon lamp. Wavelength calibration of the detector relied on spectra from mercury, hydrogen, helium, and oxygen standard emission lamps as well as a Ne-Ne laser.

Samples of anorthite glass, CaAl$_2$Si$_2$O$_8$, ~2 mm thick by 25 mm square and single crystal periclase, MgO, ~4 mm thick by 15 mm square were mounted on copper drive plates. All impact surfaces were polished to a flatness of a few nm with vapor grits to obtain a homogeneous shock front. The samples were masked to prevent spurious emissions which may arise due to edge effects. A steel sample was machined as a control to test for light not originating from the sample.

The Planck greybody formula:

$$\lambda = C_0 \lambda ^3 \exp(C_1/\lambda T) - 1)$$

where $\lambda$ is the wavelength in m, $C_0$ is the Planck constant, $C_1 = 1.44 \times 10^{-12}$ m$^2$ kg s$^{-1}$, $C_2 = 2.438 \times 10^{-8}$ mK, and $T$ is temperature in K.

3. RESULTS AND DISCUSSION

The steel control shot (#563) demonstrated that no significant light was derived from sources other than the sample during the experiments (Fig. 2).

The spectra for anorthite #3 and #4 are given in Fig. 2. The spectra passing through the data represent the best fits of the Planck greybody formula. All three anorthite shots display higher temperatures and lower emissivities than predicted on the basis of a continuum model for the material being radiating as a blackbody (Table 1).

The spectra for the three MgO shots were surprising. High temperature, low emissivity spectra similar to those for anorthite were unexpected. However, broad band time spectra centered near 700 nm were observed for all three MgO experiments (Fig. 3).

![Fig. 2. Observed spectra for shocked anorthite (glass) and control sample of steel. Trend lines running through data are best fit to Planck radiation function.](image)

![Fig. 3. Observed spectra for MgO. Spectra for MgO is almost identical to that for MgO.](image)

Anorthite undergoes a shock induced phase transformation at the pressures in question$^{1-4}$. Until now a shock induced phase transformation in periclase has not been observed to 258 GPa$^5$.

Previous work, focused on higher pressures and temperatures$^6$, showed that the minerals emit as blackbodies with emissivities close to unity and temperatures close to expected continuum temperatures predicted by standard continuum thermodynamic theory. At lower pressures observed color temperatures for NaCl, SiO$_2$, CaO$_2$, and CaO$_2$-MgO are larger than the predicted continuum temperatures by at least a factor of two, and the corresponding emissivities are much lower than those expected for a blackbody$^7$. The above observations appear to indicate the existence of three regimes of light emission which correlates with the phase state and heterogeneous deformation of brittle materials under shock compression.
Table 1. Radiative characteristics of shocked CaF$_2$, Mg silicate glass and crystal MgO.

<table>
<thead>
<tr>
<th>Shot</th>
<th>Sample</th>
<th>Projectile Vel. (km/s)</th>
<th>Shock Pressure (GPa)</th>
<th>Temperature °C</th>
<th>Emissivity</th>
<th>Maximum Radiance (W/m$^2$·sr·nm)</th>
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<td>560</td>
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<tr>
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<td>An 4</td>
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<tr>
<td>561</td>
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<tr>
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<tr>
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</table>

Fig. 4. Shock-induced spectral radiances versus channel number and wavelength for glasses at shock pressure of 33.1 GPa (shot 563) and 34.6 GPa (shot 568), respectively. Smooth curve of both spectra are the best fitted grey body radiations. The color temperatures and emissivities for both results are also shown in the figure (after Gondo and Hrones, Ref. 7).

Fig. 5. Three regimes for shock emission spectra. Characteristic radiation, heterogeneous hot bond (grey body) and blackbody shock temperature. These correspond approximately to low pressure phase, mixed phase, and high pressure phase regime.
high temperature, low emissivity observations in CaSiO$_3$, SiC, NaCl, CaCO$_3$, and CaSiO$_3$-K$_2$O are all the result of detection of shear band melting. The band and line spectra which "contaminates" these thermal spectra, particularly for CaSiO$_3$-K$_2$O (Fig. 4) and CaSiO$_3$, imply that shock-induced decomposition via a shear banding process is underlying deformation via low temperature brittle processes.

The third regime appears at high pressures and temperatures when the material (e.g., high or low pressure phase and melt) becomes sufficiently hot to maintain a continuous temperature by the shock such that no heterogeneity in the temperature is rapidly equilibrated. A limit portion of the material melts at the continuum temperature resulting in the observed high blackbody emissivity.

4. CONCLUSION

The type of radiation observed from brittle transparent minerals is dependent upon the type of deformation occurring and the phase state of the material. Three regimes are apparent: 1) at low pressures below a phase transition threshold emissive spectra are observed which may indicate deformation via brittle mechanisms; 2) beneath phase transition regions along the Hugoniot deformed is a result of a heterogeneous shear band process with some brittle failure taking place in the remaining low pressure phase regions of the material resulting in high temperature, low emissivity spectra "contaminated" by shock-induced bands and line spectra, and 3) in the high pressure - high temperature regime temperatures are rapidly equilibrated resulting in blackbody spectra and possibly another regime I may be useful for delineating the onset of a shock-induced phase transformation and for determination of the melt temperature of the high pressure phase of materials.


1. REFERENCES


