Heterogeneous Shock-Induced Thermal Radiation in Minerals

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Abstract. A 500 channel optical imaging intensified and spectral digital recording system is used to record the shock-induced radiation emitted from 400 to 821 nm from transparent minerals during the time interval that a shock wave propagates through the sample. Initial results obtained for single crystals of garnet, calcite and halite in the 30 to 40 GPa (300 to 400 kb) pressure range demonstrate greybody emission spectra corresponding to temperatures in the 3,000 to 4,000 K range and emissivity ranging from 0.003 to 0.32. In the case of garnet and calcite, distinctive line spectra, are superimposed on the thermal radiation. The observed color temperatures are a factor of 2 to 10 greater than the diagnostic temperature, calculable on the basis of continuum thermodynamics and equation of state models for the shock states achieved in the three minerals. These observed high temperatures are believed to be real. We conclude that we are detecting a large number of closed spaced high temperature shear-band regions immediately behind the shock front. A shear instability model, such as proposed independently by Grady (1977, 1980), Anantin et al. (1974a, 1974b), and Henyey (1980), in which small zones of highly deforming and molten material are produced which are the source of the detected thermal radiation and have a fractional effective area approximately numerically equal to the measured emissivity, can be used to predict an effective emissivity of 0.0065 directly behind the shock front. If shear band instability arises from viscous flow processes, Grady’s model and mineral thermal properties yield for the shocked mineral emissivities values in the range of 10^-4 to 10^-5 immediately behind the shock front.

Introduction

Shock compression techniques have provided pressure-density energy equation of state data for minerals over a wide range of pressure, which in many cases permit observation of dynamic yielding and the onset of one of more phase transitions (McQueen et al. 1967; Ahrens 1980). The applicability of shock data to problems involving the physics of planetary interiors and impact processes on planetary surfaces have been previously limited by the necessity of inferring shock state temperatures from calculated...
duced thermal radiation in NaCl has been measured at higher pressures (Kormer et al. 1965; Ahrens et al. 1982) and its phase diagram is thought to be understood. According to the holographic data of Ahrens and Oregan (1964) and Kallashnikov et al. (1973) for calcite and Simakov et al. (1974) for gypsum, both of these minerals have undergone phase changes to high pressure phases in the pressure range of the present measurement. In the case of calcite, analysis of hologram and shock temperature data, suggested that at 31 and 35 GPa this material is in the B2 high pressure phase region (Ahrens et al. 1982).

**Apparatus**

The key elements of our n-pn system to measure shock-induced radiation of matter is the EG&G Princeton Applied Research (EG&G-PARC) optical multichannel analyzer (OMA) (Fig. 1). The light emitted from material behind the shock front (in the shock-compressed state) passes through the uncompressed material and is reflected at an expendable front-surface mirror, behind the sample target. The light then is transmitted out of a vacuum tank and is focussed onto a vertical entrance slit of the OMA by a collecting lens system, 1.1, focal length and f-number are 308 mm and 2.5, respectively. The spectrometer (Jarrell-Ash 82-410, 0.25 m Unitron monochromator) was a diffraction grating (148 lines/mm, blazed at 4.0 μm) disperses the light which is subsequently imaged onto a fiber optic facet plate of a detector by lenses, L2. The magnification of the system is about 0.75. The detector is a vidicon tube with the double intensified silicon target (EST), EG&G-PARC 1227, which incorporates two electrostatically focused image intensifiers prior to the silicon diode target. The silicon diode target stores an acquired electron signal and this is "read-out" by a scanning electron beam of a vidicon tube. The vidicon tube signal is controlled, digitized, and stored by EG&G-PARC 1216 controller. The detector is gaged at the intensifier stage by using a high voltage pulse signal (EG&G-PARC 1211). The gaging pulse width and its time dependence can be digitally programmed and recorded on an oscilloscope in order to determine if the optical multichannel analyzer sampling is performed at the proper time. The OMA 2 contains a computer for waveform processor and a digitizer memory (PARC 1216) which controls, stores, displays, and is used to analyze the digital data. A small front-surface mirror placed at the side of the entrance slit of the spectrometer introduces a portion of shock-induced radiation into a Hewlett Packard PIN photodiode which operates a wide band A-C coupled pre-amplifier (SN72723). The photodiode signal is recorded on an oscilloscope in order to observe time-dependence of shock-induced radiation. Since no filter is used, the visible and near-infrared (600-1,000 nm) region contributes to the output voltage. The time resolution of this system is ~ 5 ns. A trigger pulse produced by a self-shorting pin and a pulse generator activates the system.

The silicon target of the detector is divided into a 512 × 512 array of pixel elements, which, upon photon incidence, take-off charge from an electron beam. The target array is periodically (60 μs) scanned by a moving electron beam. The beam charge loss is digitally measured yielding 500 channels of spectra data, each with 14 bit dynamic range. [Channel number versus wavelength calibration is obtained by using standard mercury and oxygen spectral lamp sources (578.0, 546.1 and 435.8 nm for Hg and 7773 nm for O₂, respectively).] Figure 2a shows the wavelength-diffraction efficiency of the OMA; versus channel in terms of the OMA. The channel width between wavelength and channel number shows some nonlinearities (2%) because the focal plane of the spectrometer is not flat. No degradation of the spectral resolution is observed as the input slit to the spectrometer is varied from 0.025 to 0.3 mm, however, for a slit width of 1.5 mm, the half-width of the 546.1 nm line is about 50 nm. Sensitivity of the system is calibrated by using a standard tungsten ribbon lamp (IR-XO, Optonic L.C.), whose radiance versus wavelength at a given current has been determined absolutely. The tungsten ribbon of the lamp was located at the position of target sample surface in order to obtain the same optical path, as in shock experiments. If the observed count at 1 th channel on the OMA at a total gating interval is N, the brightness of a sample, B(t) can be represented as follows:

\[ B(t) = \sum_{i=1}^{n} C_i \cdot N_i \cdot \lambda_i \cdot \Delta \lambda_i \]

where wavelength \( \lambda_i \) is a function of channel number as \( \lambda_i = \lambda_0 + i \cdot \Delta \lambda \). Since the brightness of the standard lamp is constant with time, the calibration factor for the i th channel

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Fig. 1: Experimental configuration of apparatus for observing shock-induced radiation spectra of initially transparent materials. Projectile velocity is determined from time intervals between interruption of He-Ne laser beams and by means of observing change in position of projectile in flash X-ray shadowgraphs taken at two times. The light from shock-compressed sample passes into the spectrometer and PIN photodiode through the apertures indicated by the arrows. Spectrum dispersed by the spectrometer is detected and accumulated on the silicon target, read out, digitized, and then stored on the memory in OMA-2 console. The detector is electronically open for a preset, 30 μs to 600 μs time duration by a gate pulse generator which is initiated by the trigger pin at the time that the shock wave impinged by the projectile impact propagated into sample. The gate pulse and shock-induced radiation change with time are recorded by oscilloscope, respectively.
and a particular time-duration, $C_1 A$, is

$$C_1 A = \frac{B'(\lambda)}{N_{A1}}$$

where $B'(\lambda)$ and $N_{A1}$ are the true brightness (radiance) and the observed count for the standard lamp, respectively.

An example of the actual calibration at 300 nm and 0.023 mm slit is shown in Fig. 3. The intensity calibration was carried out for gating times of 300, 600, and 900 ms and slit sizes of 0.023, 0.1, 0.3, and 3.5 mm. Since the electron scanning time for each of 500 channels was 60 ms and 10 times scans were used, total scanning time was 300 ms. During calibration, a mechanical shutter (1,500 s) provided a synchronized pulse for electronic gating. This was used to prevent saturation of the detector due to light leakage of the electron optics. Neutral density filters (Kodak 96), whose transmittance were measured, were used for the 0.3 and 1.5 mm wide slits to obtain optimum light intensity.

The accuracy of the system is dependent on three general factors, the accuracy of calibration, and the linearity and the reproducibility of the equipment. The reproducibility of the equipment involves noise level, gate height repeatability, gain stability, and temperature and aging effects. Actual calibration curves were obtained by averaging a number of gating times. The errors for reproducibility of the calibration factor is estimated to be 0.5 percent. The linearity seems to be better than the reproducibility of light attenuation produced via neutral density filters. However, accurate determination of linearity versus intensity for the whole dynamic range and wavelength was not carried out. Since the system position was fixed, changes of actual position of the sample free-surface on the target assembly caused minor changes of magnification. We conclude that the error for the absolute intensity was estimated to be ±5 percent which in effect, is the uncertainty in the emissivity.

The PIN photodiode detector was, in the present experiments, used as a qualitative detector and not absolutely calibrated for intensity. However, the standard tungsten lamp at (2.780 K) induces an output voltage to the oscilloscope of 60 to 80 mV.

**Shock Experiments**

The crack-free portions of single crystal gypsum samples from Selenite, Utah, were cut out along the cleavage planes and formed pellets with diagonal dimensions of 32 and 28 mm. The measured Archimedes density of 2.307 ± 0.002 Mg/m³ is close to the single crystal value of 2.305 Mg/m³. The shock propagation direction was perpendicularly to the (010) crystallographic plane. The crack-free calcite samples of Iceland Spar (Chihuahua, Mexico) were prepared as pellets along the cleavage rhombohedral faces. The surfaces correspond to (011) crystallographic plane. The Archimedes density was 2.706 ± 0.002 Mg/m³ which is again close to the single crystal value of 2.710 Mg/m³. Both flat surfaces of all the samples were polished using 0.3 µm corundum powder. Samples of artificial halite crystal were supplied by Harshaw Chemical Co. The dimension of the samples were 20 mm in diameter and 4.4 mm in thickness. These surfaces were already polished to an optical finish. The Archimedes density was 2.162 ± 0.001 Mg/m³ which is close to the 2.163 Mg/m³ single-crystal value.

The sample was mounted on a copper driver plate using a several µm thick epoxy resin bond (Catalina Labs. no. 155
<table>
<thead>
<tr>
<th>Shot number</th>
<th>Sample</th>
<th>Thickness (mm)</th>
<th>Projectile velocity (m/s)</th>
<th>Shock pressure (GPa)</th>
<th>Specimen shock transient temp. (K)</th>
<th>Delay time (ms)</th>
<th>Gating time (ms)</th>
<th>Calculated continuum limit (K)</th>
<th>Color temp. (K)</th>
<th>Emissivity (e)</th>
<th>Brightness temp. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>534</td>
<td>Gyposil</td>
<td>0.013</td>
<td>2.39 ± 0.01</td>
<td>38.2 ± 3.3</td>
<td>131</td>
<td>490</td>
<td>300</td>
<td>365</td>
<td>1.750</td>
<td>3.970</td>
<td>0.0946</td>
</tr>
<tr>
<td>528</td>
<td>Gypsum</td>
<td>0.008</td>
<td>2.49 ± 0.04</td>
<td>38.2 ± 3.3</td>
<td>130</td>
<td>190</td>
<td>190</td>
<td>619</td>
<td>1.850</td>
<td>3.920</td>
<td>0.0973</td>
</tr>
<tr>
<td>531</td>
<td>Calcite</td>
<td>0.008</td>
<td>2.36 ± 0.03</td>
<td>48.2 ± 3.3</td>
<td>122</td>
<td>190</td>
<td>190</td>
<td>619</td>
<td>1.850</td>
<td>3.920</td>
<td>0.0973</td>
</tr>
<tr>
<td>533</td>
<td>Calcite</td>
<td>0.013</td>
<td>2.41 ± 0.02</td>
<td>41.0 ± 0.6</td>
<td>993</td>
<td>190</td>
<td>190</td>
<td>600</td>
<td>2.123</td>
<td>3.720</td>
<td>0.2240</td>
</tr>
<tr>
<td>538</td>
<td>NatCl</td>
<td>0.005</td>
<td>2.28 ± 0.11</td>
<td>30.8 ± 0.3</td>
<td>453</td>
<td>190</td>
<td>190</td>
<td>600</td>
<td>3.110</td>
<td>3.010</td>
<td>0.017</td>
</tr>
<tr>
<td>599</td>
<td>NaCl</td>
<td>0.003</td>
<td>2.52 ± 0.02</td>
<td>33.5 ± 0.6</td>
<td>653</td>
<td>150</td>
<td>150</td>
<td>1,920</td>
<td>3.700</td>
<td>3.190</td>
<td>0.070</td>
</tr>
</tbody>
</table>

(a) fit to grey body equation.

and no. 6836). Both surfaces of the copper driver plate were polished to a finish of several Na-vapor filters using 0.3 mm corundum powder.

The driver plate side of the halite and calcite samples was coated with silver via standard evaporation methods. Two Dynason, CA038 self-shorting pins were mounted on the driver plate and connected to a pulse generator which triggered the whole system. Black tape with a 10 mm diameter viewing hole was used to mask the sample. In addition to the mineral samples a solid cold-steel 8 mm thick sample was prepared as a blank experiment.

The sample assembly was impacted by a tungsten flyer plate, oscillated with a 40-mm host propagating gas which then interacted with a copper driver-plate upon which the sample is mounted. The flyer plate is embedded in a Lexan plastic sandwich. The velocity of the projectile was measured by the intersection of three He-Ne laser beams propagating across the gas slab over a total distance of 75 cm, and from two flash X-ray shadowgraphs taken during the last 5 cm of projectile travel. The impedance matching method was employed to determine the high-pressure shock state in the sample, using known flyer and driver plate velocities (McQueen et al. 1970) and sample R-factors. After shock propagation, and from the stefani slit of the spectrometer, the 0.3 mm wide.

The color temperature and emissivity, T and e, were calculated for most of the observed spectra by least square fitting using the Plank blackbody radiation formula.

\[ \theta_{e} = C_{e} \lambda_{e} \exp \left( \frac{C_{e}}{\lambda_{e}} - 1 \right) \]

where \( C_{e} = 1.949 \times 10^{-4} \) m^2/kcal/degree and \( \lambda_{e} = 1.433 \times 10^{-1} \) m. The emissivity is assumed to be independent of wavelength. The equivalent blackbody brightness temperatures (assuming \( e = 1 \)) was calculated by integrating the radiation from 452 to 712 nm. Absolute brightnesses are well calibrated over this range.

For comparison purposes we show the calculated continuum shock temperatures (Table 1) for calcite, gypsum and sodium chloride. The basis of these calculations are given below.

**Results**

The shock-induced radiation for gypsum, recorded while the shock front is propagating through the sample and and no. 6836): Both surfaces of the copper driver plate were polished to a finish of several Na-vapor filters using 0.3 mm corundum powder.

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**Results**

The shock-induced radiation for gypsum, recorded while the shock front is propagating through the sample and
experiments. We conclude that the residual gas, shock
loading producing this noise signal would have a negligible
effect on the mineral experiments (Schmidt and Ahrens,
unpublished data).

The shock radiation spectra of calcite at shock pressure
of 40.4 GPa (shot no. 533) and 41.0 GPa (shot no. 533)
are shown in Fig. 7 and Fig. 8, respectively. A broad peak at
500 to 550 nm seems to be superimposed on the blackbody
spectrum in Fig. 7 (no. 533). Notably the general character-
istics of the peaked spectra superimposed on the blackbody
spectra (Fig. 7) for calcite are distinctly different than those
for gypsum (Fig. 5). For example, the well-defined peaks
at 540 and 610 nm seen in gypsum are completely absent.

For shot no. 533 (Fig. 8) the 500 to 550 nm broad peak
is anomalously large. Therefore, we have chosen not to
attempt to fit a temperature to the radiation spectra for
shot no. 533. Notably the shock states achieved in shot
no. 535 and no. 553 were similar. Since the gating time of
shot no. 533 is twice that of no. 535, whereas the delay
time is the same, photons from the rapidly increasing
portion of the brightness versus time profile of Fig. 9 are
accumulated in the ISISG target. We, therefore, conclude
that the rapidly increasing intensity portion of the signal
observed in Fig. 9 is the result of a sub-luminous signal
from a portion of the sample which has unloaded but was
in the field of view of ISISG with wavelengths of ~310 nm.

The shock-induced radiance from shocked halite crys-
tals are reasonably well fit by theoretical greybody curves
as shown in Fig. 10. For this mineral, brightness tempera-
tures are relatively close to the expected ones, whereas the
color temperatures are shock higher and close to the upper
limit of continuum shock temperature. Although the shock
pressure of shot no. 539 is considerably higher than that
of shot no. 538, the radiance intensity or the brightness
temperatures is slightly lower. The oscilloscope trace for time
Fig. 9a, b. Shock-induced radiance changes as a function of time for calcite at shock pressure of (a) 4.0 GPa and (b) 4.0 GPa (shot no. 537 and no. 533, respectively). S, A, and G have the same meaning as in Fig. 6.

Fig. 10. Shock-induced spectral radiance versus channel number and wavelength for halite (NaCl) at shock pressure of 30.9 GPa (shot no. 538) and 35.3 GPa (shot no. 539), respectively. Smoother curves for both spectra are the best fitted greybody radiance. The color-temperatures and emissivity for both results are also shown in the figure. Integrated intensities from 352 nm to 741 nm correspond to the brightness temperatures of 2,938 and 1,930, respectively.

Fig. 11. Shock-induced radiance change as a function of time for NaCl crystal at shock pressure of 35.3 GPa (shot no. 539). S, A, and G have the same meaning as in Fig. 6.

dependence of radiance intensity (Fig. 11) indicates a ringing and broad peak, at which time presumably most of the emitted photons were accumulated. Again the line spectra emitted from this mineral are clearly different than those observed from either calcite or gypsum.

Continuous Temperatures
We have calculated the continuum temperatures which are those that would exist if the irreversible energy were deposited on the shock front and uniformly distributed. We use the methods outlined in Ahrens et al. (1969), and McQueen et al. (1967), in the case of isentropic and Birch-Murphy-Hughoniot equations of state, respectively. The continuum shock temperature and the irreversible energy density \( \rho \) corresponding to thermodynamic equilibrium are useful for characterizing wavelength, or spacing, of deformation shear bands (Gibbs 1977) (discussed in the next section). Continuum temperatures are calculated in Table 1, in the pressure range of the present experiments. For gypsum we assume a transition to a high pressure phase of zero pressure density of 3.07 g/cm\(^3\) using the phase transformation parameters and metastable Hugoniot equations of state of Bažolov et al. (1976) (Table 3). Similarly, we employ the high pressure phase (density: 3.0 to 3.1 g/cm\(^3\)) equations of state properties for calcite (Vigirda and Ahrens 1982). The uncertainties in the calculated shock temperatures indicated for CaCO\(_3\) (Table 1) are typical of those for other minerals as well. In the case of NaCl analysis of previous shock wave data (Ahrens et al. 1982) suggests that the present experiments were carried out in the B1-B2 or B2 phase regimes. Recent work by Sato-Sorensen (1982) suggests that the zero pressure density of the B2 phase may be considerably higher than assumed in the present models. The equation of state parameters used to calculate the theoretical shock temperatures of Table 1 are indicated in Table 2. \( \Delta T \) is an upper limit to the continuum shock temperature was also obtained (Table 1) by assuming that all the Hugoniot energy goes into shock heating.
Table 2. Assumed High Pressure Phase Equation of State Parameter

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Initial density (g/cm³)</th>
<th>Bulk modulus, K (GPa)</th>
<th>Grüneisen parameter</th>
<th>Transition energy, STP (10⁶ eV/atom)</th>
<th>Specific heat (10² erg/K K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃</td>
<td>3.0-3.1</td>
<td>75-95</td>
<td>3.5-4.1</td>
<td>1.5</td>
<td>0.02-0.2</td>
</tr>
<tr>
<td>NaCl</td>
<td>2.32</td>
<td>43</td>
<td>3.6</td>
<td>2</td>
<td>0.16</td>
</tr>
<tr>
<td>CaSO₄·2H₂O</td>
<td>3.07</td>
<td>115</td>
<td>2.84</td>
<td>3.1</td>
<td>1.854</td>
</tr>
</tbody>
</table>

* Models II-IV, Vázquez and Altherr (1982)
* Model B, Altherr et al. (1982)
* Parameters of metastable Hugoniot shock-particle velocity relation, Bataille et al. (1976)

Discussion

The observation of low-level light signals yields low apparent bulk emissivities. The measured spectra can be fit with extremely high color temperatures, greybody curves. Strong and distinctive line spectra are superimposed in the case of gypsum and calcite. The greybody observations strongly support the hot spot isomorphous yielding and phase transition models of Grady (1980) and Horie (1980). Both models envision that because of the strong temperature, β dependence of viscosity, η, of dissolution dissolution under rapid instabilities accounts for the extensive shear banding observed in metal and the numerous planar features in non-metallic crystals shocked to states above the Hugoniot elastic limit. (Stöffler 1972; Klein 1965; Chao 1967; Ananian et al. 1974). Other experimental evidence of isomorphous deformation is evidenced by the in situ X-ray observation of shock deformed single crystals (Kondo et al. 1979) and discovery experiments Affholter et al. (1968) and Juinott et al. (1977). In Grady’s (1980) analyses he assumed a viscosity of the form

\[ \eta(6, \theta, v) = \frac{\tau_0}{\theta} \exp \left( -\theta / (6 - \theta) \right) \]

where \( \eta \) and \( \theta \) is a reference viscosity at a reference temperature. Here \( v \) is related to the activation energy of the viscous flow process and is given as \( v = \frac{\tau_0}{\theta} \), where \( \tau_0 \) is the gas constant and \( \theta \) is the activation energy of the flow process. He demonstrated that shear instabilities grow at a maximum rate given by

\[ \tau = \frac{\gamma}{\gamma_0} \frac{\tau_0}{\theta} \frac{\theta}{\theta} \]

and the wavelength of the maximum shear instability growth is given by

\[ \delta = \frac{2\pi}{\lambda} \frac{\rho_0 C_0}{\tau_0} \]

where \( \rho_0 \) is the density, \( \tau_0 \) is the strain rate, \( C_0 \) is the specific heat and \( \lambda \) is the thermal diffusivity.

Since the appropriate viscosity \( \eta \) and temperature dependence of viscosity is known to vary widely on account of numerous deformation mechanisms which act in minerals, the parameters \( \eta_0 \) and \( \eta_0 \) in Eqs. (4), (5), and (6) are poorly constrained. Grady points out, however, that planar features with spacings of ~0.02 to 0.002 mm are observable in all minerals which undergo phase changes at relatively low temperature such as SiO₂, CaCO₃, and plagioclase. These spacings suggest that zones with temperature as high as 1,000 K, are achievable only at 2.5 GPa in calcite and the time scale of cooling-off of shear bands instabilities via Fourier conduction is ~10⁻¹⁰ to 10⁻⁹ s.

Two issues which we can address within the framework of this model are:

1. To examine the range of effective viscosities inferred and determine if these lie within plausible bounds.
2. To determine if the spacing of shear bands and time scales of thermal diffusion from local shear bands are such that the present values of greybody emissivity can be explained.

Using values typical of the present experiments of 10⁶ s⁻¹ for \( \theta_0 \), 2.3 gn/m² for \( \rho_0 \), 0.001 cm²/s for \( \lambda \), 0.8 J/g for \( C \), shear band spacing of (d) of 0.02 to 0.002 mm, and \( \theta_0 \) of 40 kJ/mol, values of \( \eta_0 \) varying from 6 x 10¹⁰ to 6 x 10¹⁰ P are obtained. For a large value of \( \eta_0 \) of 356 kJ/mol (Turcotte and Schubert 1982), viscosities of 3 x 10¹¹ to 3 x 10¹² P are calculated. The range of equivalent viscosities inferred here appear to us to be reasonable since they lie between the values inferred for minerals in the upper mantle ~10¹² P (Pattee 1981) and above those inferred from shock wave rise times ~10¹⁰ P (Jeans and Altherr 1979). The maximum distance, \( d \), and time scale, \( t \), required for a given temperature, \( T_o \), to thermally diffuse outward from a shear band region is given by (Grady 1977)

\[ d = \frac{T_o}{\eta_0} \]

where \( \eta_0 \) is the continuum wave rest of dissipated energy density and \( T_o \) is the temperature achieved upon isometric compression to the same density as the shock. The

\[ T_o = T_c - T_c \]

where \( T_c \) is the continuum Hugoniot temperature.

If \( T_o = T_c \), Eq. (8) reduces to

\[ d = \frac{\theta_0}{360 \pi \tau_0} \]

which, for example, yields time scales of 3 x 10⁻¹⁰ s (comparable to the present experiment) and thermal diffusion distances (d) of ~10⁻⁷ mm for \( d = 0.001 \) mm. Applying the shear band heating model to the experiments when the sampling time or shock transit time through the sample is in the order of 10⁻¹⁰ to 10⁻¹² times longer than the peak temperature duration suggests that temperatures on the order of the continuum shock temperatures are conducted outward from shear bands on a very short time scale. As demonstrated in Table 1, we are measuring several times the continuum shock temperature. Thus, if we are viewing a very thin layer immediately behind the shock front, the emissivity should be given by the ratio of the areas as follows:

\[ \frac{A}{A_0} = \frac{\theta_0}{\theta} \]
Substituting Eqs. (7), (10), and (11) in (12), we yield the result

\[ c \sim 1/(8 \pi \sigma) = 0.00651 \]

(12)

which is comparable to values observed which vary between 0.017 and 0.0025 (Table 1).

We conclude on both the basis of low values of the emissivities and the rapidly varying radiation versus time signals recorded by the PND diode that the thermal radiation detected is emitted immediately behind the shock front. We infer that the time variation of light recorded reflects either spatial variations in the pre-shock density and possible variations in deformation characteristics. Finally, we suggest that the measured increase in optical emission observed by Lyngaa (1982) at low shock pressure upon entrance of the shock front into MgSiO3 crystals and in the present experiments, especially upon emergence of the shock front at the sample free surfaces arise from crystal defects which were induced upon sample preparation.

Kittel (1968) have determined the brightness temperatures of NaCl, CsBr, and LiF from the measured light fluxes in the 27 to 104 GPa range. These authors assumed that the emissivity was unity. The present results suggest that in all cases the effective emissivity is much lower. For example, in the case of NaCl at 40 GPa, Kittel (1968) calculated a temperature of 2,120 K whereas their observed brightness temperatures were 2,700 K and 2,450 K at 478 and 624 cm. However, the brightness temperatures observed here for NaCl is as low as 1,830 ± 1,930 K. Their results are likely to be influenced by the effect of detecting high temperatures within a gap between driver plate and sample (Kondo et al., 1982).

The PND photodiode result shows an interesting ringing signal in the case of halite. In the shock-pressure range of the present experiments, we believe we have driven NaCl into the B1-B2 mixed phase or B2 high pressure phase regime. This ringing may be strongly related to this phase transition. Similar phenomena have been observed at higher pressures in regions where quartz shocked into the austenite may be melting (Lyngaa et al., 1983). That the brightness temperature at 35 GPa is lower than that of 31 GPa may be related to the embay change of the B1-B2 phase transition and is predicted by Ahrens et al. (1982).

Conclusions

The light emission spectra of gypsum, calcite and halite have been recorded for time durations of ~300 ns with a photon and wavelength calibrated multichannel spectral analyzer during the period (~600-800 ns) that shock waves of 30 to 40 GPa amplitude are driven through these minerals. All materials demonstrate very low emissivities, in the 0.003 to 0.02 rate and apparent color temperature between 3,000 and 4,000 K whereas the temperature expected on the basis of adiathermic calculations ranges from 400 to 1,900 K. Shock induced changes to high pressure phases are presumed to take place at the shock front. The phase changes are believed to be related to transition with 35, 15, and 3 percentage density increases (at STP) for the high pressure phase in the case of gypsum, calcite, and halite, respectively (Bastian et al. 1970; Vigirdas and Ahrens 1982; Liu and Basset 1973). Recently, Sato-Sorensen (1982) has fit NaCl B2 phase pressure-volume data and inferred a larger (27%) density increase at STP for the B1- B2 transition. Associated with compression to high pressure data, we have to assume that a series of small highly deformed shear unstable regions are produced which are truly hot and the source of the high color temperature observed in all experiments. We have, by way of comparison, carried out some preliminary experiments on MgO which is not believed to MnO (from 0-MnO transition phase in their pressure range (Schmidt and Ahrens, unpublished). From the initial MgO results it is not clear whether the shear heating model is necessarily associated with phase changes. The low level of the emissivity observed reflects the low concentration of these hot shear band regions. A low value of the emissivity ~0.0065 is inferred from simple application of the shear band heating model. This is comparable to those we obtained from fitting observed spectra to theoretical greybody radiation curves. These results suggest that all previous relatively low temperature (~<3,000 K) brightness temperature determinations of either the shock (Kittel et al. 1968) or post-shock temperatures (Raikes and Ahrens 1979) have overestimated the continuum temperatures. Superseded on the observed greybody spectra, we line spectra which appear to be characteristic of the minerals in the case of gypsum and calcite. Thermochemical processes may account for the radiation from these crystals. The present results strongly support the thermal shear band deformation model for shock compression of solids (Grady 1977; 1980; Howe 1980). In the case of calcite this model is further supported by recent gas recovery experiments in which some 0.02 percent (mass) of CO and CO2 is released upon shock to 18 GPa (Boslough et al. 1982). Shock induced vaporization occurs as a result of exposure to far lower shock speeds than certain continuum thermodynamic calculations would predict.

Acknowledgments. We appreciate the interest and help of A. Sawaoka of Tokyo Institute of Technology, and W. Ginz, E. Gelse, M. Longinotti, M. H. Mitas, J. Vigirdas, and M. Bollhorn of Cavitech. The paper has benefited from the helpful comments of M. J. Jenkins (Texas A&M) and an anonymous reviewer. Research was supported by NASA, Grant No. NGL-05-000-165, Contribution No. 3680, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.

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Received October 1, 1981