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TEMPERATURES OF SHOCK-INDUCED SHEAR INSTABILITIES AND THEIR RELATIONSHIP TO FUSION CURVES

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Abstract. New emission spectra for MgO and $CaAl_2Si_2O_8$ (glass) are observed from 430 to 820 nm. Taken with previous data, we suggest that transparent solids display three regimes of light emission upon shock compression to successively higher pressures: (1) characteristic radiation such as observed in MgO and previously in other minerals, (2) heterogeneous hot spot (greybody) radiation observed in $CaAl_2Si_2O_8$ and previously in all transparent solids undergoing shock-induced phase transformations, and (3) blackbody emission observed in the high pressure phase regime in NaCl, SiO_2, CaO, $CaAl_2Si_2O_8$, and Mg_2SiO_4. The onset of regime (2) may delineate the onset of shock-induced polymorphism whereas the onset of regime (3) delineates the Hugoniot pressure required to achieve local thermal equilibrium in the shocked solid. We also propose that the hot spot temperatures and corresponding shock pressures determined in regime (2) delineate points on the fusion curves of the high pressure phase.

Introduction

Although shock wave techniques have been used to study the pressure-density relations of important minerals, shock temperatures have, to date, largely been calculated.

Recently, methods for temperature measurement have been described by Lyzenga and Ahrens (1979) who used a six channel optical pyrometry system, and Sugiura et al. (1982) who used a 500 channel spectrophotometer to measure radiance over the optical range. Kondo and Ahrens (1983) and Kondo et al. (in press) constructed a similar system with radiance magnitude calibration (Fig. 1) to measure the shock temperatures of various minerals. They found much higher temperatures and lower emissivities than expected for a continuum thermodynamic state in SiO_2, NaCl, $CaSO_4 \cdot 2H_2O$ and $CaCO_3$. Their results implied that localized shear deformation (Grady, 1980) occurred in the pressure range over which minerals undergo shock-induced phase changes. Here we report on emissions from shocked $CaAl_2Si_2O_8$ (glass) and single-crystal MgO and a new hypothesis on the significance of the color-temperature of shear bands.

Experimental

Our experiments were conducted using a 40 mm gun to launch tungsten flyers which impacted copper drivers which held the samples. Projectile velocities were determined by laser beam interruption and flash X-ray photography (Fig. 1).

As the shock travels through the sample, radiation propagates through the unshocked portion of the sample to a mirror which reflects the light out of the tank. The light is focused upon a diffraction grating and is dispersed to illuminate a charge coupled detector. The detector is gated to collect radiation only while the shock front is near the sample center. The light beam gives, via a photodiode, an analog signal of the total intensity versus time.

Wavelength calibration of the system relies upon standard gas emission lamps and a He-Ne laser. Radiation intensity calibration was obtained with a standard tungsten ribbon lamp.

Samples of $CaAl_2Si_2O_8$ glass (Corning Co.) and single crystal MgO (Norton Co.) were epoxied on the driver plates. Driver plates and samples were ground to an optical finish and polished.

Color temperatures and emissivities were determined by a least squares fit of the data to the Planck formula:

$$R = \varepsilon C_1 \lambda^{-5} [\exp (C_2/\lambda T)-1]^{-1} \quad (1)$$

where R is the spectral radiance in $W/m^2 \cdot ster \cdot nm$. Here λ is the wavelength, ε is the wavelength independent emissivity, c_1 = 1.191 x 10^{-16} $Wm^2/ster$, C_2 = 1.438 x 10^{-2} mK, and T is the temperature in K.

Continuum temperatures were calculated (Table 1) by the method of Ahrens et al. (1969) using the parameters given by Jeanloz and Ahrens (1980) for $CaAl_2Si_2O_8$ and Vassiliou and Ahrens (1981) for MgO. Pressures were determined by the impedance match method using Hugoniots of $CaAl_2Si_2O_8$

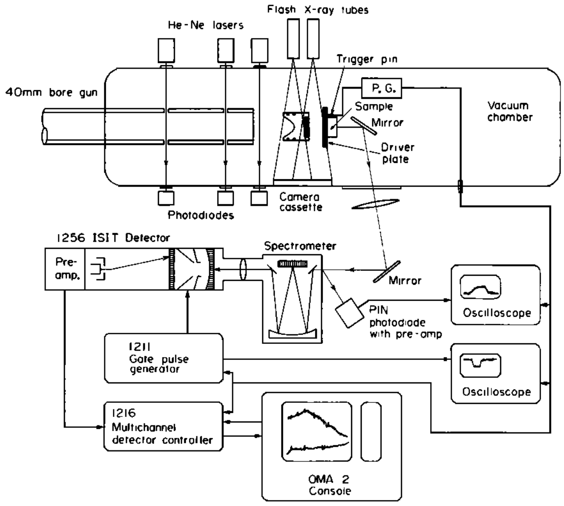

Fig. 1 Apparatus for observing shock-induced spectra of transparent materials. The light travels along the paths indicated. Sample mask eliminates free surface effects. Gate pulse and time variation of the shock-induced radiance are recorded by oscilloscopes (after Kondo and Ahrens, 1983). Data stored in OMA2.

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TABLE 1. Radiative characteristics of shocked $CaAl_2Si_2O_8$ glass and crystal MgO.

Shot	Sample	Projectile Vel. (km/s)	Shock Pressure (GPa)	Theoretical Continuum Temperature °K	Color Temp. °K	Emissivity	Maximum Radiance μW/ mm²·ster·nm
560	An#1	2.39	37.5	1576	3340	0.007	27.0
562	An#3	2.49	39.7	1686	3135	0.028	45.8
564	An#4	2.44	38.6	1600	2845	0.15	104.6
563	Steel	2.36	85				7.4
565	MgO#1	2.38	60.5	490			147.7
566	MgO#2	2.20	55.1	447			121.1
568	MgO#3	2.43	62.3	534			153.2

(Jeanloz and Ahrens, 1980), and MgO (Vassiliou and Ahrens, 1981).

Results and Discussion

A steel control shot (#563) was performed to determine if significant light could be generated by the shock produced in the 80 μm air environment of the impact chamber (Fig. 2a). The smooth curves passing through the anorthite data (Fig. 2a) represent the best fit greybody curves. The greybody fit to An#1 (not shown) was dubious due to the high noise to signal ratio. The data for An#3 and An#4 fit the greybody formula well and it can be confidently stated that they are thermal spectra. These color temperatures are twice as high as those predicted as described above. The emissivities are much lower than if the material radiated as a blackbody (Table 1). These results are similar to those found in shocked NaCl, $CaCO_3$, $CaSO_4 \cdot 2H_2O$, and SiO_2 (Kondo and Ahrens, 1983; Kondo et al., in press).

The spectra from the three MgO shots (Fig. 2b) were surprising as a lower temperature greybody spectra was expected. Instead, a band emission

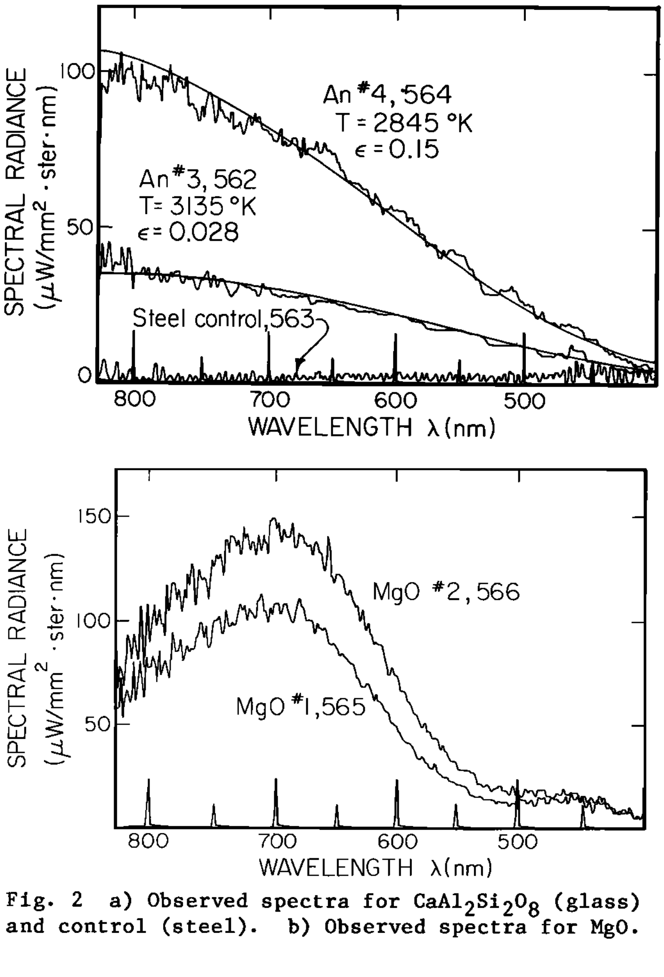

Fig. 2 a) Observed spectra for $CaAl_2Si_2O_8$ (glass) and control (steel). b) Observed spectra for MgO.

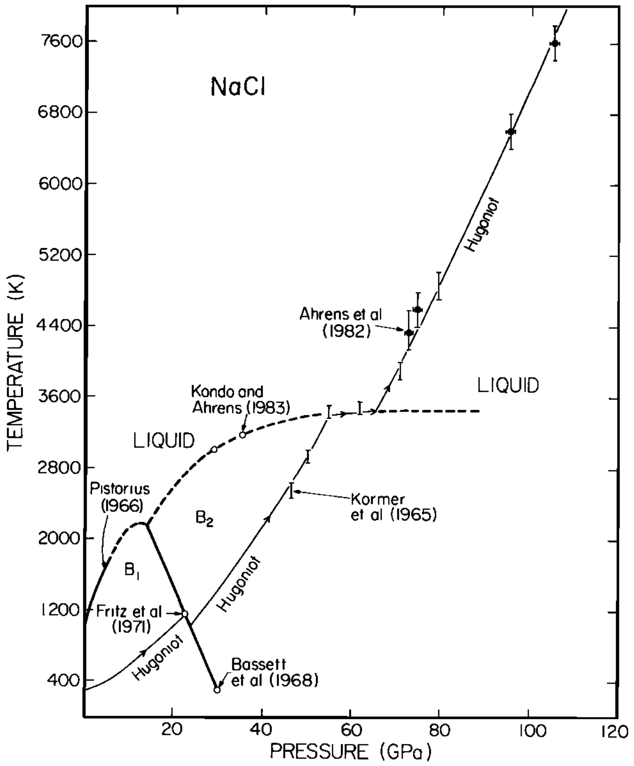

Fig. 3 Proposed phase diagram of NaCl based on temperatures of Kondo and Ahrens (1983), Hugoniot temperatures of Kormer et al. (1965), Ahrens et al. (1982), see also Lyzenga (1980). DTA melting point determination (Pistorius, 1966), Hugoniot pressure-density data (Fritz et al., 1971) and high pressure x-ray diffraction (Bassett et al., 1968).

spectra centered at 700 nm was observed. MgO does not undergo a phase change to pressures of 258 GPa (Vassiliou and Ahrens, 1981).

The high temperature and low emissivity of anorthite is interpreted as resulting from localized high temperatures produced by nonuniform deposition of energy due to shear instabilities. We believe these arise due to phase transformation as suggested by Grady et al. (1975, 1980). This phenomenon is also found by Brannon et al. (1983) who photographed light emitted by crystallographically controlled shear bands in (x-cut) crystal quartz. In fused quartz the onset of hot spot luminescence was observed by Brannon et al. (1983) to correlate with the phase transformation to stishovite.

We suggest, therefore, that there are three regimes of light emission from minerals: (1) The characteristic radiation regime, (2) the heterogeneous hot spot (greybody) regime, and (3) the blackbody equilibrium shock temperature regime.

For minerals such as MgO (i.e. at pressures below a phase transition) only characteristic radiation is emitted. In regime (1) emissions are unique for each mineral, even when superimposed on radiation from regime (2) (as in Kondo and Ahrens, 1983; Kondo et al., in press).

In the heterogeneous hot spot regime, as small regions of the solid collapse inward, nucleated by the growth of denser high pressure phase, shear instabilities are produced from stored strain energy. This occurs until a thin layer of melt coats the high pressure phase with the result that the shear band temperature is constrained to the solidus of the high pressure phase. The low emissivity is related to the small fraction of melt. We speculate that, at successively higher pressures in a mixed phase regime, the amount of melt remains small resulting in low emissivities.

In regime (3) for which data for minerals have been reported above 2000 K, by Kormer et al.

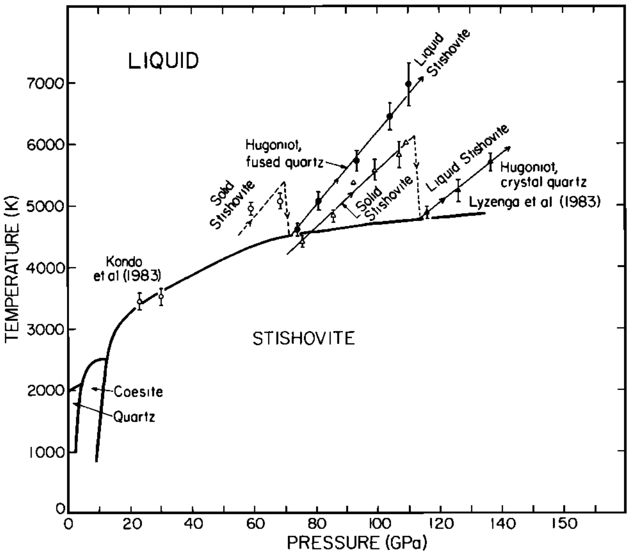

Fig. 4 Proposed high pressure phase diagram for SiO_2. Stishovite liquid boundary based on hot spot temperature (Kondo et al., in press, 1983) and Hugoniot temperatures (Lyzenga et al., 1983) (after Ahrens et al., 1982).

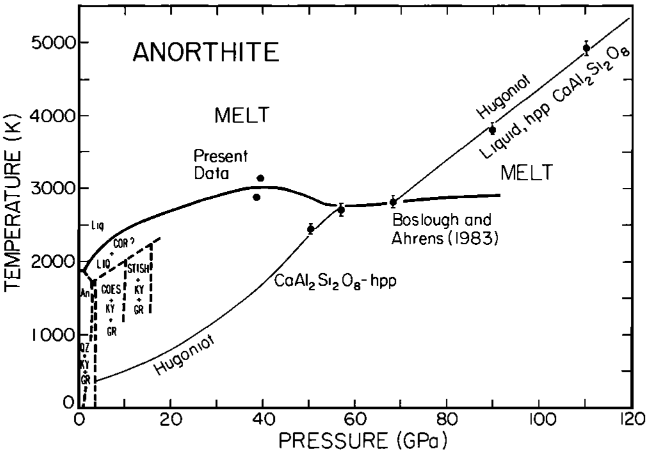

Fig. 5 Proposed phase diagram for $CaAl_2Si_2O_8$. Liquid $CaAl_2Si_2O_8$ boundary inferred from present data and Hugoniot temperature data of Boslough and Ahrens (1983). Lower pressure phase relations are complex (see e.g. Hariya and Kennedy, 1968; Lindsley, 1968; Goldsmith, 1980; and Liu (1978)).

(1965), Lyzenga and Ahrens (1980), Lyzenga (1982), Ahrens et al. (1982), Lyzenga et al. (1983), and Boslough and Ahrens (1983), the material becomes sufficiently heated to a continuum temperature by the shock, such that thermal heterogeneities are rapidly equilibrated. The observed emissivities are close to unity.

The best example of radiation in the heterogeneous regime yielding data pertinent to establishing the fusion curve is for the B_2 phase of NaCl (Kondo and Ahrens, 1983, Figure 3). Here, and also for SiO_2, Figure 4, the greybody spectra of Kondo and Ahrens (1983) are contaminated by characteristic radiation. For NaCl the B_2-liquid boundary is close to that suggested by Bundy (1971) and consistent with the B_2 liquid phase boundary inferred from the shock temperature measurements of Kormer (1965). The P-T trajectories of the Hugoniot in Figure 3 for B_2 and liquid phase are those of Ahrens et al. (1982). The two least characteristic radiation contaminated fused quartz shots (Kondo et al., 1983) represent the melting point of stishovite at 23 and 30 GPa (Fig. 4).

The inferred hpp anorthite solidus in P-T space (Fig. 5), based on our anorthite data, demonstrate that these high temperature-low emissivity observations are consistent with the hypothesis of constraint of shear band temperature to the solidus.

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