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SHOCK WAVE EQUATIONS OF STATE OF CHONDRITIC METEORITES

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We have obtained shock compression data for Murchison and Bruderheim chondritic meteorites. Data for Murchison suggest that the Hugoniot states are described by a smooth curve to ≥90 GPa, having $\rho_0 = 2.656$ Mg/m^3, $K_{S0} = 24.2\pm.7$ GPa, $K' = 4.17\pm.10$, and constant $\gamma = 1.0$. The data for Bruderheim suggest more complicated behavior. A mineral mixture model consistent with the Bruderheim data suggests that the Hugoniot state is a low pressure phase below 25 GPa, with $\rho_0 = 3.555$ Mg/m^3, $K_{S0} = 146$ GPa, $K' = 2.53$, and constant $\rho\gamma = 7.11$ Mg/m^3; and a high pressure phase above 65 GPa, with $\rho_0 = 4.40$ Mg/m^3, $K_{S0} = 225$ GPa, $K' = 3.25$, and constant $\rho\gamma = 7.485$ Mg/m^3.

INTRODUCTION

Because hypervelocity impacts are a significant process in planetary evolution, accurate knowledge of the shock compression properties of the materials involved is important for models of such events. While most existing shock compression data for relevant materials are for terrestrial rocks, the impactors are extraterrestrial objects with compositions similar to meteorites, chondrites being the most abundant of these. Here, we study the shock compression behavior of two chondritic meteorites and present suggested equations of state.

EXPERIMENTAL PROGRAM

Shock wave equation of state (EOS) experiments were performed on samples of the Murchison carbonaceous chondrite (bulk density = 2.244±.087 Mg/m^3) and Bruderheim hypersthene chondrite (bulk density = 3.337±.011 Mg/m^3). The samples were cut into rectangular slabs with the surfaces ground flat and parallel and were placed on driver plates, with buffer materials against the rear surfaces of the samples (Fig. 1). These assemblies were impacted by projectiles launched

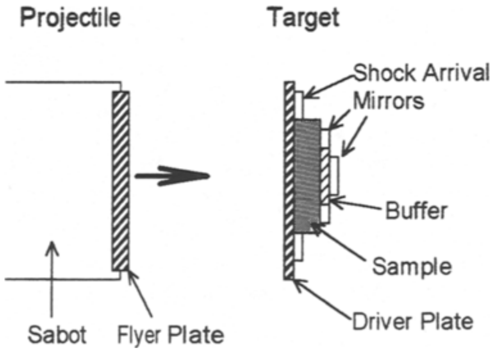

FIGURE 1. Schematic of experimental arrangement.

TABLE 1. Experimental Results for Bruderheim and Murchison Meteorites.

		Shock State				**Release State**		
Sample and Shot #	**Initial Density (Mg/m^3)**	**Particle Velocity (km/s)**	**Shock Velocity (km/s)**	**Density (Mg/m^3)**	**Pressure (GPa)**	**Particle Velocity (km/s)**	**Pressure (GPa)**	**Density (Mg/m^3)**
Bruderheim	3.3247	.757[a]	5.111[a]	3.902[a]	12.86[a]			
900	(.0024)	(.017)	(.024)	(.016)	(.30)			
		.773[b]	4.285[b]	3.920[b]	13.08[b]	2.586	0	1.98
		(.012)	(.058)	(.016)	(.24)	(.092)		(.07)
Bruderheim	3.3490	1.967	6.571	4.780	43.29	3.115	24.7	3.57
897	(.0025)	(.009)	(.072)	(.028)	(.43)	(.407)	(3.6)	(.80)
Bruderheim	3.3293	2.416	6.990	5.088	56.22	3.712	32.0	3.76
LGG309	(.0034)	(.008)	(.033)	(.020)	(.21))	(.074)	(1.1)	(.16)
Bruderheim	3.3465	3.913	9.433	5.719	123.53			
LGG306	(.0032)	(.006)	(.035)	(.020)	(.39)			
Murchison	2.3914	.398[a]	2.997[a]	2.757[a]	2.85[a]			
885	(.0027)	(.016)	(.019)	(.018)	(.12)			
		.736[b]	2.862[b]	3.197[b]	5.15[b]	3.237	0	.65
		(.008)	(.021)	(.018)	(.12)	(.719)		(.21)
Murchison	2.1761	2.163	5.057	3.802	23.80	2.601	19.7	3.23
1016	(.0027)	(.037)	(.017)	(.050)	(.41)	(.061)	(.7)	(.32)
Murchison	2.1852	3.046	6.386	4.178	42.51	4.129	38.5	1.88
LGG255	(.0032)	(.014)	(.036)	(.032)	(.24)	(.059)	(.9)	(.38)
Murchison	2.2242	4.503	8.458	4.757	84.72	5.869	72.2	2.79
LGG254	(.0049)	(.008)	(.092)	(.067)	(.80)	(.074)	(1.6)	(.31)

[a] Elastic Precursor
[b] Plastic Wave

from the Caltech 25 mm two-stage light gas gun and 40 mm propellant gun. Shock arrivals at the surfaces of target components were detected on streak camera records by the disappearance of reflections from rear-surface mirrors placed against the target. The shock and release states were determined via the impedance matching method.

Experimental Results

Table 1 presents the experimental results. The U_s-u_p projections of the shock Hugoniot curves (Fig. 2) can be described by straight lines:

$$U_s = C_0 + su_p \qquad (1)$$

with C_0 = 3.11±.06 km/s and s = 1.62±.02 for Bruderheim and C_0 = 1.87±.07 km/s and s = 1.48±.03 for Murchison. The data for Bruderheim show some evidence that the U_s-u_p Hugoniot might be more complicated than a single straight line. There is no such evidence in the Murchison data.

Both meteorites exhibit two-wave shock behavior at low stresses. In Murchison, the stress of the precursor wave is 2.85±.12 GPa and is consistent with interpretation as an elastic wave. The stress level of the precursor in Bruderheim is 12.86±.30 GPa, which is unexpectedly high for an elastic wave. We suggest that the double-wave structure in this case may indicate a sluggish phase transformation, such as is seen in carbonates (1).

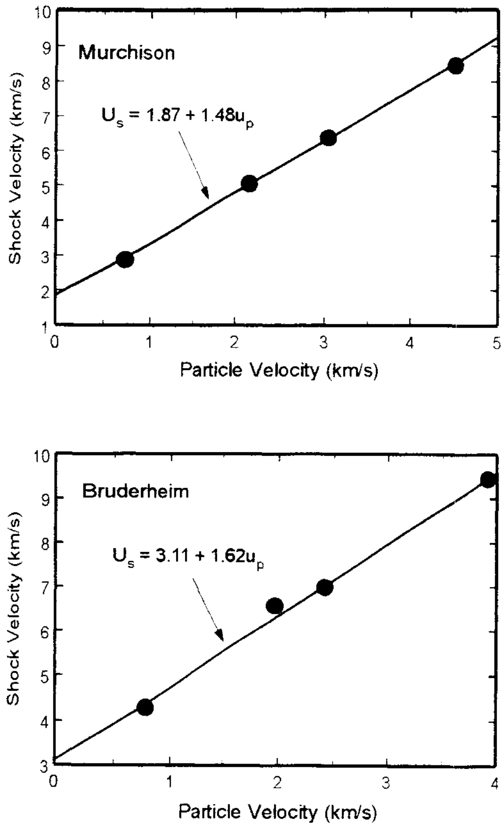

FIGURE 2. Shock velocity-particle velocity projections of the experimental data with linear fits.

EQUATIONS OF STATE

We wish to constrain effective equations of state that can be used in models of planetary impact processes. Both meteorites contain a number of minerals that undergo known shock-induced phase changes. The deviations of the Bruderheim data from linearity suggest such phase changes. The smooth linear trend followed by Murchison data in Fig. 2 can be described by a single "phase," but probably simply does not reflect the complex behavior of the individual components under shock loading. It is important to note that, as these samples are polymineralic aggregates, "phase" is used here to imply an assemblage of phases.

Murchison Equation of State

Since the data suggest that Murchison does not undergo any detectable phase transformations up to at least 90 GPa, we can fit the present data to a single effective equation of state. The zero-pressure nonporous density of Murchison, based on mineral norms calculated from the composition (2), is 2.656 Mg/m^3, indicating that the present samples are ~16% porous. A fit to the shock wave data (Fig. 3a), gives the isentropic bulk modulus and its pressure derivative as K_{S0} = 24.2±.7 GPa and K'= 4.17±.10. The best fit was obtained under the assumption that the thermodynamic Grüneisen parameter has a constant value of $\gamma = 1.0$.

Composition-Based Estimates

As an alternative to fitting EOS data directly, we can attempt to estimate the shock compression behavior of a material using knowledge of the composition. We use simplified mineral norms, which are based on published composition data (2,3), to estimate the Hugoniot curves of both meteorites. In both cases, we treated the Hugoniot volume of the bulk material as the mass-weighted mean of the Hugoniot volumes of the constituent minerals (4). No attempt was made to correct for the temperature differences between the Hugoniot states of different minerals, since thermal expansion is a second-order effect.

Figure 3a shows the results of the mineral mixing estimate for Murchison. The model consistently overestimates the specific volume of the Hugoniot state. The model also requires both low- and high-pressure phase stability regions, based on the behavior of the constituent minerals, while there is no evidence for multiple phases in the present data. The calculated Hugoniot curves resemble those of serpentine, which is often used as an analog for Murchison and other carbonaceous chondrites. The present results suggest that serpentine, even though a major constituent of Murchison, is a poor analog and that the high content of hydrous phases gives rise to complicated shock compression behavior.

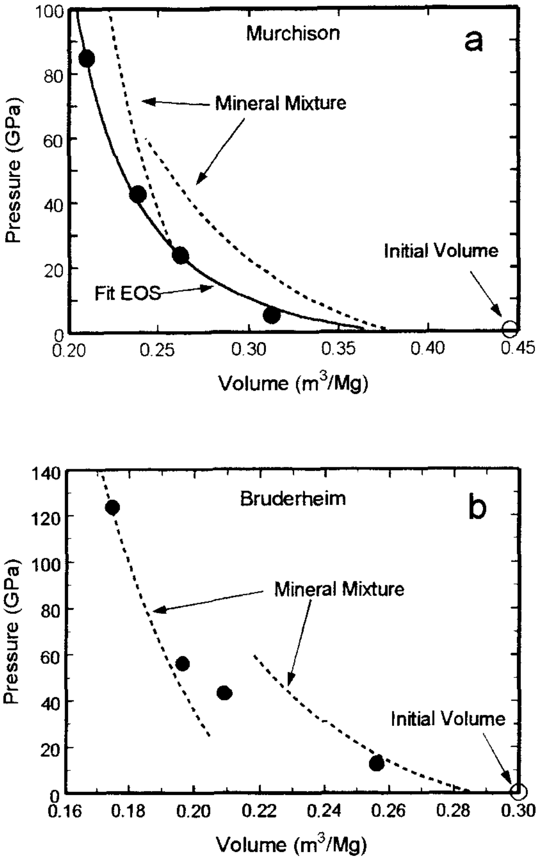

FIGURE 3. (a) Pressure-volume Hugoniot data for Murchison, compared to Hugoniot curves predicted by the fit equation of state and mineral mixture model. (b) Pressure-volume Hugoniot data for Bruderheim, compared with Hugoniot curves predicted by the mineral mixture model.

Figure 3b shows the estimated Hugoniot curves for Bruderheim. In this case, the mineral mixture model gives a good match to the experimental data. Based on these results, we can attempt to obtain estimates of effective EOS parameters for Bruderheim low and high pressure phases. For the low pressure phase, using $\rho_0 = 3.555$ Mg/m^3, based on measured Archimedian densities of the samples, we get $K_{S0} = 146$ GPa, $K' = 2.53$, and constant $\rho\gamma = 7.11$ Mg/m^3. For the high pressure phase, we get $\rho_0 = 4.40$ Mg/m^3, $K_{S0} = 225$ GPa, $K' = 3.25$, and constant $\rho\gamma = 7.49$ Mg/m^3, with an STP transition energy from the low pressure phase of 1.25 MJ/kg. The intervening pressure region, from ~25 GPa to ~ 65 GPa, represents a mixed-phase region.

CONCLUSION

We have obtained shock compression data for Murchison and Bruderheim chondritic meteorites. The data for Murchison suggest that the Hugoniot state is described by a single curve up to at least 90 GPa, having $\rho_0 = 2.656$ Mg/m^3, $K_{S0} = 24.2 \pm .7$ GPa, $K' = 4.17 \pm .10$, and constant $\gamma = 1.0$. Comparison with a mineral mixture model suggests that such models do not work well for carbonaceous chondrites and that serpentine is a poor analog for carbonaceous chondrites.

Bruderheim data suggest a more complicated Hugoniot, but are insufficient to constrain equations of state. A mineral mixture model consistent with the data suggests that the Hugoniot state consists of a low pressure phase below 25 GPa, with $\rho_0 = 3.555$ Mg/m^3, $K_{S0} = 146$ GPa, $K' = 2.53$, and constant $\rho\gamma = 7.11$ Mg/m^3; and a high pressure phase above 65 GPa, with $\rho_0 = 4.40$ Mg/m^3, $K_{S0} = 225$ GPa, $K' = 3.25$, constant $\rho\gamma = 7.485$ Mg/m^3, and transition energy of 1.25 MJ/kg.

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REFERENCES

1. Ahrens, T. J., and Gregson, V. G., *J. Geophys. Res.* **69**, 4839-4874 (1964).
2. Jarosewich, E., *Meteoritics* **6**, 49-52 (1971).
3. Duke, M., Maynes, D., and Brown, H., *J. Geophys. Res.* **66**, 3557-3563 (1961).
4. Al'tshuler, L. V., and Sharipdzhanov, I. I., *Izv. Earth Physics (Engl. Trans.)* 167-177 (1971).