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Characterization of Antarctic micrometeorites by thermoluminescence

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Abstract–In order to explore the nature and history of micrometeorites, we have measured the thermoluminescence (TL) properties of four micrometeorites, three cosmic spherules, and one irregular scoriaceous particle, that we found in a survey of 17 micrometeorites. These micrometeorites have TL sensitivities ranging from 0.017 ± 0.002 to 0.087 ± 0.009 (on a scale normalized to 4 mg of the H3.9 chondrite Dhajala). The four micrometeorites have very similar TL peak temperatures and TL peak widths, and these distinguish them from CI, most CM, CV, CO, and ordinary chondrites. However, the TL properties of these micrometeorites closely resemble those of the unusual CM chondrite MacAlpine Hills (MAC) 87300 and terrestrial forsterites. Heating experiments on submillimeter chips of a CM chondrite and a H5 chondrite suggest that these TL properties are have not been significantly affected by atmospheric passage. Thus we suggest that there is no simple linkage between these micrometeorites and the established meteorite classes, and that forsterite is an important component of these micrometeorites, as it is in many primitive solar system materials.

INTRODUCTION

Micrometeorites are extraterrestrial particles, <1 mm in size, collected on the surface of the Earth, largely in Antarctica (Maurette et al. 1986, 1991) or in the atmosphere (Brownlee 1985). Their origin could be the asteroids, the Moon, Mars, or comets (Bradley et al. 1988; Love and Brownlee 1993), and they make up the majority of the mass accreted to the Earth from space (Love and Brownlee 1993). Being so small, they are subject to Poynting-Robertson drag and might be more representative of the primitive material of the solar system than their larger counterparts, the meteorites (Kortenkamp et al. 2001). Small particles can pass through the atmosphere unaltered, but particles in the 50 μm to 1 mm range may be unaltered, partially altered, or completely melted depending on entry velocity and angle.

The compositions, mineralogy, and textures of micrometeorites (Taylor et al. 2000), and particularly Antarctic micrometeorites, have been reported by many authors (Beckerling et al. 1992; Klöck et al. 1992; Greshake et al. 1996; Gounelle et al. 1999, 2005; Christophe Michel-Lévy and Bourot-Denise (1992); Noguchi and Nakamura 2000). Micrometeorites are mostly chondritic (Kurat et al. 1992b; Engrand and Maurette 1998), having mineralogies and compositions similar to carbonaceous chondrites but lower in Na, Ni, Ca, S, Se, and Zn (Kurat et al. 1992a, 1994; Maurette 1992). Typically, they consist of iron oxide, iron sulfide, and anhydrous silicate phases (Kurat et al. 1994; Christophe Michel-Lévy and Bourot-Denise 1992; Genge et al. 2008). The effects of atmospheric heating on the mineralogy of micrometeorites have been reported by many authors (Rietmejier 1996; Toppani and Libourel 2003; Greshake et al. 1998; Nozaki et al. 2006; Tomioka et al. 2007; Genge et al. 2008). Such measurements suggest that volatile elements, like S, Zn, Ga, and Se will be lost by atmospheric heating, and that temperatures above 800 °C can convert phyllosilicate phases to olivine and pyroxene.

Induced thermoluminescence (TL) properties have been uniquely successful in evaluating the nature and metamorphic history of ordinary chondrites, CM chondrites, CV chondrites, and CO chondrites, E chondrites, lunar samples, and basaltic meteorites (Sears et al. 1980, 1982, 1991a, 1991b, 1993, 1995b; Sears and Weeks 1983; Guimon et al. 1984, 1985, 1995, 1988; Keck and Sears 1987; Keck et al. 1987; Ninagawa et al. 1992; Matsunami et al. 1993). Essentially, TL is the light produced by a substance as it is heated and it depends on crystal structure and the presence of defects and impurities (e.g., Mn^{2+} in Ca sites in feldspar, or Mn^{2+} and Cr^{3+} in forsterite or enstatite, cause luminescence, Fe^{2+} is a quencher). The strength of induced TL measurements (draining the natural TL and applying a standard test dose) is their extraordinary sensitivity, these

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minerals being detectable in amounts that would be missed by normal mineralogical and petrographic methods. The technique also allows a certain level of mineral identification because the details of TL production vary with the mineral responsible. Here we report an induced TL study of four micrometeorites collected at Cap Prudhomme, Antarctica (Maurette et al. 1991). Our objective was to explore the value of thermoluminescence as a means of comparing them with the known meteorite classes and thereby contribute to an understanding of their origin and history. Early phases of this work were reported at conferences (Sedaghatpour et al. 2008; Sears et al. 2008).

EXPERIMENTAL

Seventeen micrometeorites with size between 100–160 µm were examined as possible subjects for this study, and four were selected because of their especially high levels of TL and thus worthy of a detailed study. There were six cosmic spherules (CS) and eleven scoriaceous micrometeorites (SC). For thermoluminescence measurement, the micrometeorites were placed in a copper pan in a Daybreak Nuclear and Medical systems TL rig. Heating rates were 7.5 °C/s and the TL produced between room temperature and 500 °C was recorded. After removal of natural TL by a brief heating to 500 °C in the TL apparatus, the samples were exposed to a 200 mCi ^{90}Sr beta source for 3 minutes and the induced TL measured. Repeat measurements were made. We measured TL maximum for an identifiable peak, the width of that peak, measure as the full-width at half its maximum intensity (FWHM), and the temperature at which the peak appears. The peak height is normalized to the TL signal from 4 mg of a non-magnetic portion of the Dhajala H3.9 ordinary chondrite; this is referred to as the "TL sensitivity."

In order to evaluate the effects of atmospheric passage on the TL properties of micrometeorites, heating experiments were performed on six submillimeter fragments of a meteorite with no measurable TL (CM chondrite MAC 88100) and six fragments of a meteorite with a very high TL sensitivity (the H5 ordinary chondrite Jilin). In this way we could detect both the formation of TL phosphors, perhaps by the dehydration of hydrated minerals, and their removal by oxidation or melting. Heating was performed in Lindburg tube furnace with a temperature range of 200 to ~1200 °C in air at atmospheric pressure. The temperature was controlled with an Omega OS562 thermal probe with an accuracy of ±1 °C. After their preheating TL properties were measured, samples were placed in the furnace on a heated quartz rod, removed after 30 s, and allowed cool in the atmosphere.

RESULTS

Induced TL was below the detection limit for thirteen of our particles, but strong signals were detected for four, designated SC2, CS2, CS3, and CS4 (Fig. 1). The TL sensitivities for our micrometeorites are shown in Table 1. Values range from 0.017 to 0.087 but are generally nearer the lower end of this range, sometimes with a factor of two differences between duplicate measurements. The uncertainty on the TL sensitivity measurements—determined from the replicate measurements of similar sized Semarkona matrix samples and the signal-to-noise ratio on the raw data for these particles (~10)—is only about 10%. This suggests that the micrometeorites are heterogeneous and tumbled between measurements.

The glow curves for the four micrometeorites are shown in Fig. 2. To a first approximation, the overall shapes of the glow curves are similar to those observed for most chondritic materials, consisting of two major peaks, the lower peak (at 150–200 °C) being the most intense in three of the micrometeorites, and the higher peak (at ~400 °C) being the most intense for the scoriaceous micrometeorite SC2 which has only a weak peak in the 140–240 °C region.

Peak temperatures and peak widths are also listed in Table 1. Peak temperatures range from 165 to 211 °C, the values for duplicate measurements on the same micrometeorite being within about 10%. Three of the particles have very similar values, the scoriaceous micrometeorite SC2 perhaps being slightly higher, but the relative weakness of this peak makes this uncertain. TL peak widths tend to be less uniform because of interference from the higher peak, but are within 30–40% for duplicates and in the range 85 to 133 °C for all the particles.

The results of our heating experiments are shown in Fig. 3. The CM chondrite MAC 88100, which showed no measurable induced thermoluminescence before heating, was unaffected by the heating process (Fig. 3a). The noise on the glow curve (mostly thermal noise) is equivalent to a TL sensitivity detection limit at the 3σ level of about 0.002 under these experimental conditions, about a factor of 10 lower than our weaker micrometeorites.

The H5 chondrite Jilin (Fig. 3b) showed no change in TL properties when heated at 200, 400, 600, and 800 °C, the slight variation from curve to curve reflecting heterogeneity in the six submillimeter Jilin fragments. However, heating at temperatures of 1000 and 1180 °C caused a complete loss of signal detectable above the noise.

SAMPLE DESCRIPTIONS

Following measurement of their TL properties, the micrometeorites were imaged by ESEM (Philips Model XL30) and analyzed with an EDX attachment under high vacuum and running at 10 and 20 keV. Our analyses were made on whole particles, and are therefore subject to large uncertainties and are sensitive to weathering products on the surfaces. Images for those with measurable TL are shown in Fig. 1 and will be described below.

Table 1. Induced thermoluminescence data for four Antarctic micrometeorites.[a]

Sample	Description	Size (µm)	TL sensitivity (Dhajala = 1)	Peak temperature (°C)	FWHM (°C)
SC2	Irregular	~150 × 117	0.036 ± 0.004	211 ± 21	107 ± 16
	Scoriaceous		0.018 ± 0.002	185 ± 18	133 ± 20
CS2	Ellipsoid	~170 × 140	0.065 ± 0.007	185 ± 18	85 ± 12
			0.087 ± 0.009	165 ± 16	96 ± 14
CS3	Spherule	~155 × 140	0.036 ± 0.004	185 ± 18	125 ± 18
			0.017 ± 0.002	180 ± 18	85 ± 12
CS4	Spherule	~160 × 150	0.019 ± 0.002	175 ± 17	92 ± 14
			0.038 ± 0.004	185 ± 18	89 ± 13

[a]Data for two independent measurements are quoted. Uncertainties were not estimated for individual measurements but experience with similar materials suggests that 1 uncertainties are ~10% for TL sensitivity, ~10% for peak temperature, and ~15% for peak width. TL sensitivity is the induced TL intensity normalized to that of 4 mg of bulk sieved Dhajala powder.

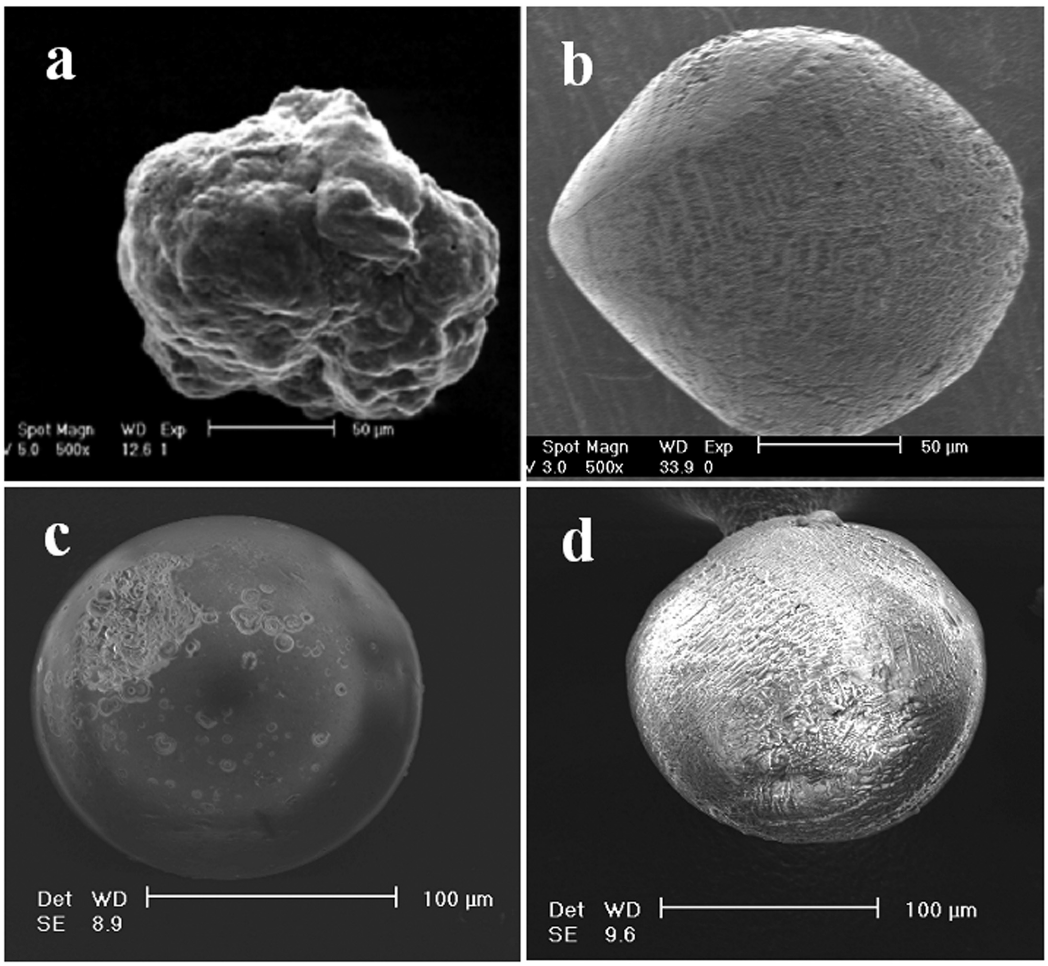

Fig. 1. Scanning electron images of the micrometeorites that were found to have high TL levels and are the subject of the present study. a) Irregular scoriaceous micrometeorite SC2. b) Cosmic spherule CS2. c) Cosmic spherule CS3. d) Cosmic spherule CS4. Scale bars for Figs. 1a, 1b, 1c, and 1d, are 50 µm, 50 µm, 100 µm, 100 µm, respectively.

Micrometeorite SC2 (Fig. 1a) is a scoriaceous particle that is an irregular shape ~150 µm by ~120 µm. The blocky texture suggests that it is coarse grained and our EDX data suggests the presence of forsterite and iron oxides. Thus it is possibly a porphyritic olivine coarse-grained scoriaceous micrometeorite (Genge et al. 2008).

Micrometeorite CS2 (Fig. 1b) is a cryptocrystalline spherule similar to those shown in Fig. 1i-l of Genge et al. (2008). Such objects are usually contain Fe-rich fine-grained olivine crystals and grains that survive melting and form crystallization nuclei.

Micrometeorite CS3 (Fig. 1c) is a glassy spherule similar

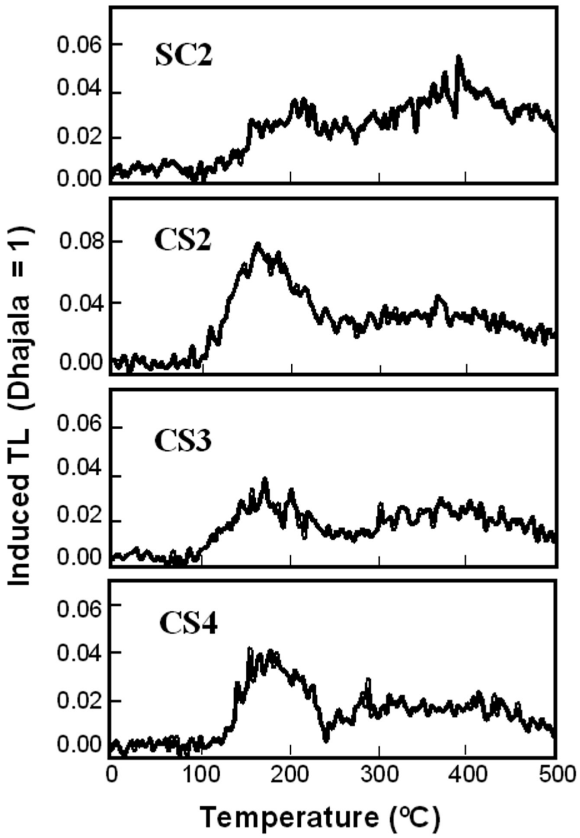

Fig. 2. Induced TL "glow curves" (plots of light produced as a function of laboratory heating temperature) for the four micrometeorites shown in Fig. 1. As with most extraterrestrial materials, the curves consist of a peak in the region 150–200 °C and a broader peak in the region 320–420 which are referred to as the "low" temperature and "high" temperature TL. The curves for the three cosmic spherules are very similar, but the scoriaceous particle shows a higher high temperature TL, relative to the low temperature TL, compared to the others.

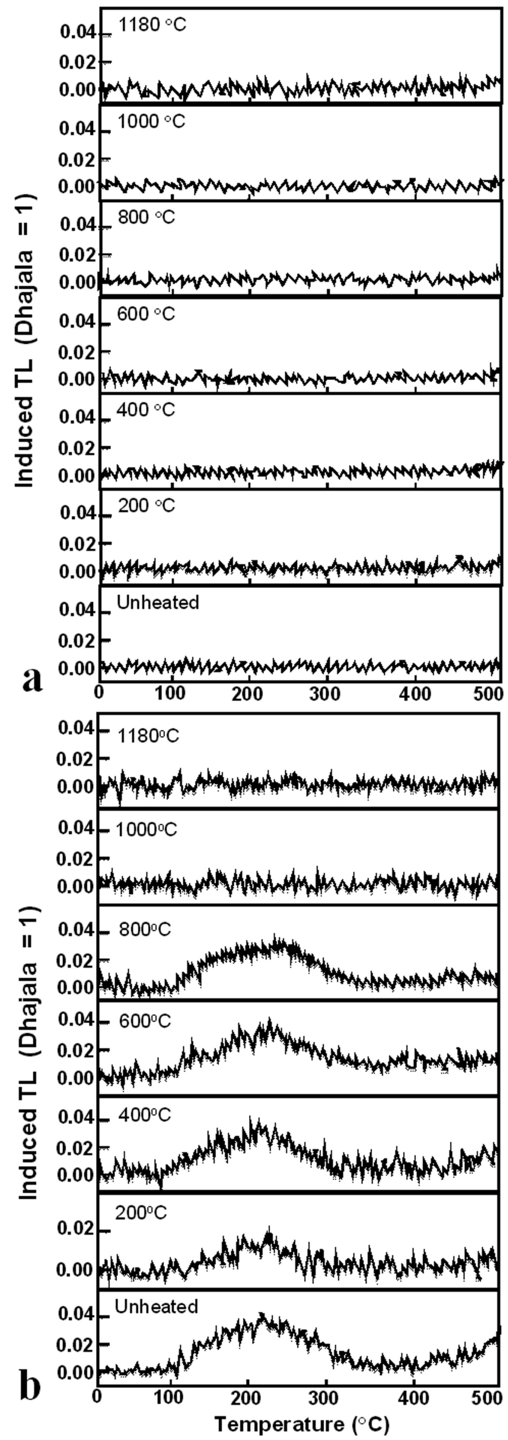

Fig. 3. Glow curves for submillimeter samples of the CM chondrite MAC 88100 (a) and the H5 ordinary chondrite Jilin (b) heated in air for 30 s at the temperatures indicated. The heat treatment was unable to cause a TL signal to appear in the CM chondrite that initially had no TL, and the heat treatment was unable to affect the TL of the ordinary chondrite with a strong initial TL signal until the heating reached ≥1000 °C, when the sample was no longer able to produced detectable TL. We suggest that in the case of the ordinary chondrite, temperatures this high caused melting of the feldspar responsible for the TL signal.

to that shown in Fig. 1e of Genge et al. (2008). These objects frequently contain FeNi metal grains and vesicles. Our EDX analysis was consistent with normative Mg-rich pyroxene and olivine.

Micrometeorite CS4 (Fig. 1d) is identical in external appearance to the S-type spherule shown in Fig. 1i of Genge et al. (2008), which is also a cryptocrystalline texture. Such spherules normally contain submicron crystals and significant submicron magnetite. Olivine crystal can grow from the surface inward producing a knobby surface called turtleback, and this appears to be the case with CS4. Again, our EDX analyses are consistent with this mineralogy.

All our particles contained large amounts of normative hematite (10–60%), presumably due to surface weathering or atmospheric oxidation. However, we also detected normative silicates olivine and pyroxene in all the particles, in one instance a metal grain, and normative feldspar (~10%). Feldspar has only rarely been observed in micrometeorites (Christophe Michel-Lévy and Bourot-Denise 1992) and we assume this component identified by the norm calculation is actually glass.

DISCUSSION

We will first compare the present data with similar data for CO chondrites, CM chondrites, CV chondrites, and the ordinary chondrites. Then we will discuss the mineralogical implications of these data and then we will discuss the results of our heating experiments and implications for the effect of atmospheric passage on the TL of our micrometeorites. Finally we will briefly discuss lessons learned from this study on the measurement of the TL properties of small particles.

Before proceeding, we mention that our present TL measurements involved light coming from the surface because, while the test dose of radiation can penetrate the whole object, these objects are largely opaque. Consistent with this, on one occasion, we saw considerable variability in the level of TL produced by one of the micrometeorites, CS4, as it tumbled in the apparatus between measurements. However, this did not affect the shape of the TL glow curve and any of the conclusions discussed here. The surface is also usually weathered, and amorphous materials are generally poor at displaying TL, so we suspect that our TL signal is coming from essentially unweathered grains that intercept the surface. We suspect that if we were to break open some of the nonluminescent micrometeorites, we would obtain a signal. However, here we focus on the four micrometeorites that display a strong signal.

Comparison of Induced TL Properties with Those of Known Chondrite Classes

We will not discuss CI chondrites because they do not produce a measurable TL signal, and we will not discuss enstatite chondrites because of their highly characteristic and distinct TL properties.

Figure 4a shows representative glow curves for CO chondrites and the CM chondrites (Keck and Sears 1987). The natural TL survey of Antarctic meteorites included many CM chondrites that showed no measurable TL (Myers et al. 1990). However, MAC 87300, MAC 87301, and MAC 88107 (the last not shown in Fig. 4a) are unusual paired CM chondrites that produce TL. Sears et al. (1991) suggested that this paired trio of MAC meteorites should be considered CM3.0, CM3.1, and CM3.1 chondrites, respectively, as many of their properties resembled those of CO3.0–CO3.2 chondrites.

The CO chondrites show a range of fairly well-understood TL properties that reflect the range of metamorphism experienced by this class (Keck and Sears 1987). The properties they display reflect the formation of feldspar by the crystallization of glass and that the feldspar is in the low-temperature form. The hummocky structure of the CO3.0 and CO3.2 is not well understood, but probably represents a mixture of minerals including forsterite and the minerals found in refractory inclusions. Cathodoluminescence (CL) micrography of these meteorites is consistent with the TL being due to forsterite and refractory phases (Sears et al. 1991), and the CL of Murchison (which has been studied in some depth) suggests that forsterite is abundant and luminescence in these meteorites although in a form not suitable for detection by TL (Sears et al. 1993). Most probably, the emission is at longer wavelengths than we can detect in our TL apparatus where heat filters are used to suppress black body radiation from the sample.

Figure 4b compares peak temperatures for the CO and CM chondrites, and compares them with peak temperatures for the micrometeorites. The CO chondrites show a transition from a major peak at ~250 °C to ~125 °C as the dominant phosphor changes from small amounts of primary high-temperature feldspar to metamorphism-produced low-temperature feldspar. The micrometeorites plot in a similar range of peak temperatures to the CM chondrite, suggesting similarity to each other and dissimilarity to the CO chondrites. The high-temperature peaks in the micrometeorites, seen occasionally in the CO chondrites, especially the least metamorphosed members, resemble the peaks observed in refractory inclusions from Allende and are probably due to refractory minerals in these samples.

The CV chondrites have thermoluminescence properties that are similar to those of CO chondrites, reflecting the presence of refractory phases (with a peak at ~350 °C in Fig. 5a), high-temperature feldspar (whose peak is at ~220 °C in Fig. 5a) and low-temperature feldspar (where the peak is at ~110 °C in Fig. 5a). The relative proportions of these and the overall TL sensitivity of the CV chondrites reflect changes caused by metamorphism (Keck and Sears 1987; Sears et al. 1991). The refractory inclusions show similar trends in which the metamorphic differences appear to exist from one inclusion to another. The peak temperatures for the low temperature TL for the micrometeorites (~175 °C) are clearly plotting intermediate to the feldspar peaks in the CV chondrites, again suggesting discrete differences (Fig. 5b). The high-temperature peaks in the micrometeorites also appear to be plotting at higher values than the high temperature peaks for the CV chondrites (~400 °C compared with ~350 °C), suggesting that if refractory minerals are responsible for these peaks, they are distinct from those of CV chondrites.

The ordinary chondrites probably have the best-understood TL properties of any meteorite class. In terms of TL sensitivity, the micrometeorites are comparable to 4 mg samples of petrographic type 3.2–3.4 ordinary chondrites (Table 1). This is surprisingly bright for such small particles. However, the data for their TL peak temperatures and TL widths (Fig. 6) suggests little, if any, connection with the ordinary chondrites with their dominant feldspar thermoluminescence. Ordinary chondrites plot in two discrete

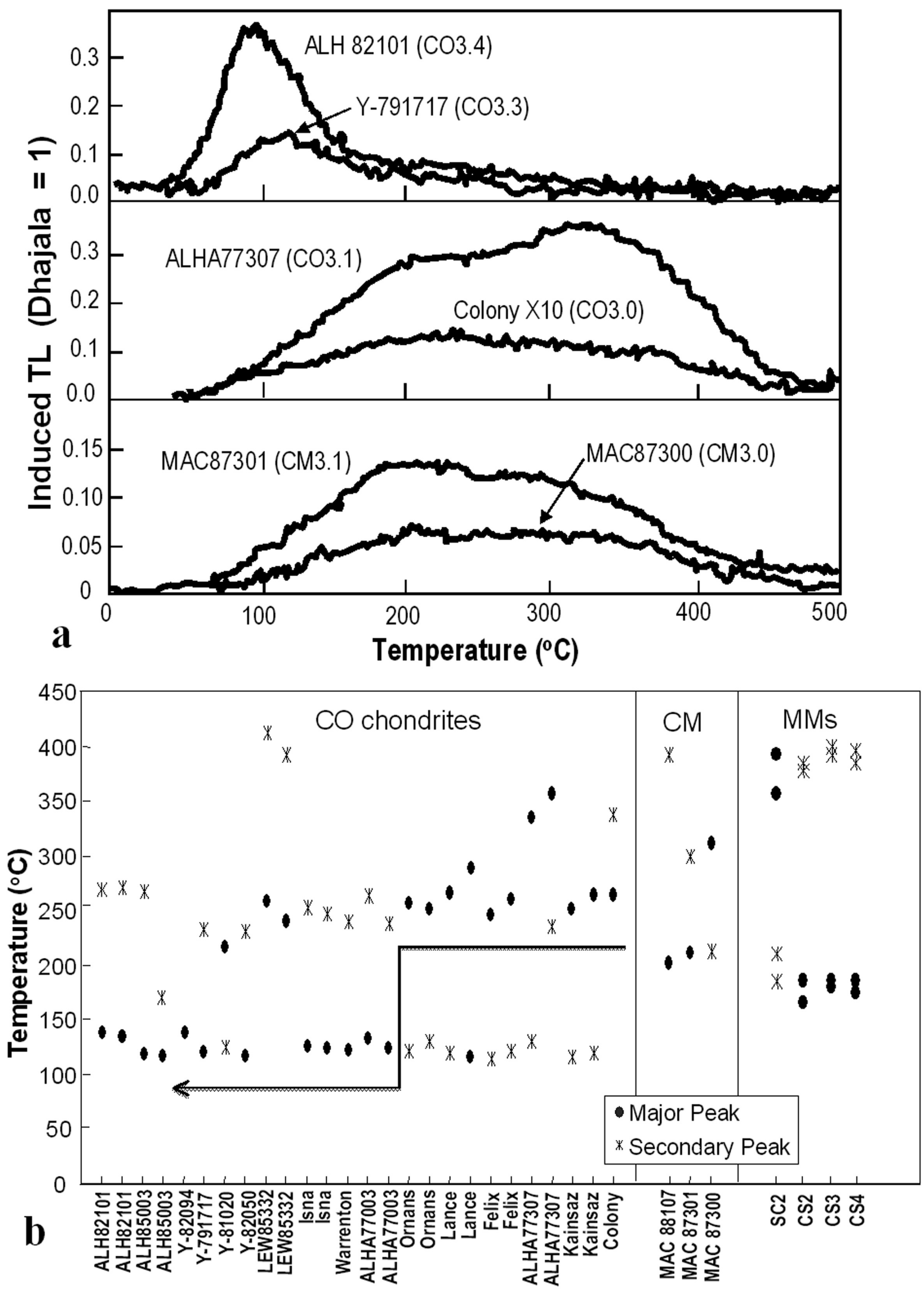

Fig. 4. a) Representative TL glow curves for CO chondrites, of varying metamorphic type, and the paired CM chondrites MAC 87300 and MAC 87301 that are unlike other CM chondrites in displaying a significant TL signal. Induced TL peaks in these samples tend to be at ~100 °C, ~200 °C, and ~350 °C (Sears et al. 1991a). Detailed studies of the TL properties of these meteorites and phases separated from them suggest that these peaks are due to low-temperature (metamorphism-produced) feldspar, high-temperature (primary) feldspar, and refractory phases like melilite, respectively (Sears et al. 1991a, 1995). b) A detailed comparison of peak temperatures shows that while the micrometeorites are very similar to each other, they are distinct from the CO chondrites but resemble the anomalous CM chondrites (including a third paired member MAC 88107).

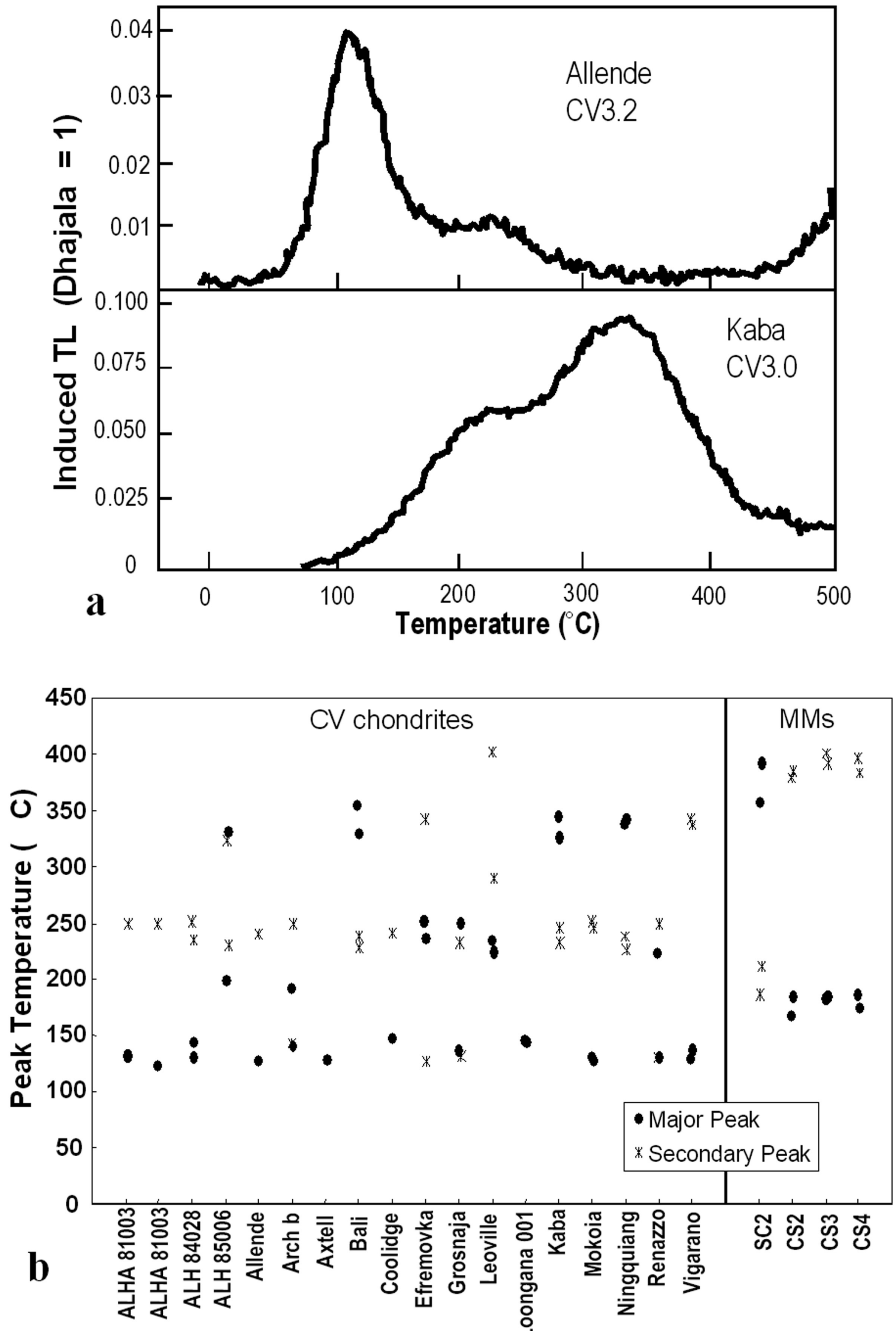

Fig. 5. a) Representative glow curves for CV chondrites showing very similar properties to those of the CO chondrites in Fig. 4 (Sears et al. 1995). b) A detailed comparison of peak temperatures shows that in addition to being distinct from CO chondrites, the present micrometeorites, at least for the low-temperature TL, are distinct from CV chondrites. However, the micrometeorites display induced TL at ~400 °C which may be analogous to the ~350 °C peak frequently shown by the CV chondrites and attributed to refractory phases.

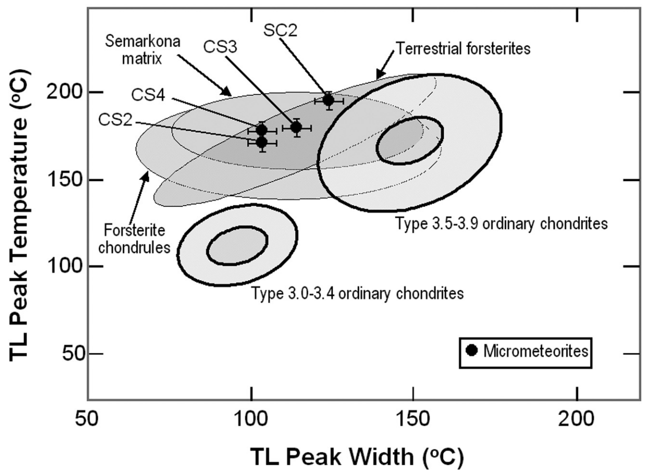

Fig. 6. A useful way of comparing the present data with that for ordinary chondrites is to consider both the peak temperature and the peak width. Ordinary chondrites plot in two fields, depending on the structural state of their feldspar, which is determined by thermal history. These fields are 1σ and 2σ variances shown in an unpublished compilation of all available TL data by Jeff Grossman (see Craig and Sears 2009, for more details). Seven terrestrial forsterites (Craig and Sears, Forthcoming), six matrix fragments from Semarkona (for which the phosphor is also thought to be forsterite, see Craig and Sears 2009), and 11 forsterite-bearing chondrules from Semarkona (Sears et al. 1995a), plot in the fields indicated. The presence of the micrometeorites in the forsterite fields would suggest that the phosphor responsible for the low-temperature TL in these micrometeorites is forsterite.

regions in Fig. 6, the lower petrographic types (types <3.5) plot in the lower field and the higher types (types 3.5 and above) plot in the higher field. The micrometeorites plot to higher temperatures and smaller widths than the ordinary chondrites.

Forsterite in Micrometeorites

The luminescence properties of solids are governed by energy transitions in a crystal lattice, the phosphor, which contain appropriate luminescence centers, usually transition metal ions but sometimes a structural defect (Garlick and Gibson 1948; McKeever 1985). Additionally, TL requires sites in the crystal lattice capable of trapping electrons that can be released by heating the sample. Removing the electrons naturally present in the traps and then providing a standard test dose of radiation in the laboratory provides a means of investigating the number and nature of the phosphors, and to characterize the sample and its history (Sears and Hasan 1986; Sears 1988). Some kinds of materials (for example quartz) have TL peaks whose induced TL properties can be affected by large radiation doses. This is a rare phenomenon only observed to any extent with the 110 °C peak of quartz, and it is unlikely that it affected the present samples. An important difference between micrometeorites and the chondrite samples is that the chondrite samples were almost certainly part of much larger bodies in space and were shielded from radiation. However, a detailed analysis of this issue was performed when extraterrestrial materials were first studied by TL, and we found that their induced TL properties were remarkably unresponsive even to the highest radiation doses (Sears 1980).

The most common phosphor for TL in extraterrestrial materials is feldspar, where Mn^{2+} in the Ca^{2+} sites causes both electron traps and luminescent centers (Geake et al. 1973). Thus the conversion of feldspathic glass to feldspar causes a 10^5-fold increase in TL sensitivity (Sears et al. 1980). Metamorphism also causes the conversion of low-temperature (structurally ordered) feldspar to high-temperature (disordered) and the resulting changes trap depth causes changes in TL properties reflected in the two ordinary chondrite fields in Fig. 6 (Guimon et al. 1984, 1985). Refractory inclusions from Allende show a movement for the dominant TL peak from ~100 °C, to ~200 °C, to ~400 °C as the dominant phosphor converts from low-feldspar, to high-feldspar, to melilite during metamorphism (Sears et al. 1995b). In the enstatite chondrites, it is the enstatite that produces TL with many relatively narrow peaks (Zhang et al. 1995).

Forsterite is well known for its cathodoluminescence (CL), which is usually red but occasionally blue (Steele et al. 1985; Steele 1986). Trace amounts of any transition metal iron, such as Mn^{2+} and Cr^{3+} can cause CL and TL emission by forsterite. Small amounts of Fe^{2+} in the lattice (greater than ~1 mol%) quenches the TL of most minerals (Geake et al. 1973), including olivine, pyroxene, and feldspar, and this process can also have value in understanding the history of these samples (Batchelor and Sears 1991). Our EDX analysis and the Genge et al. (2008) descriptions of micrometeorites with similar morphologies are consistent with a major presence of olivine in these micrometeorites.

Also shown in Fig. 6 are the fields occupied by seven terrestrial forsterites obtained from a variety of volcanic and metamorphic environments on Earth (Craig and Sears 2009), ~100 μm fragments of Semarkona matrix in which forsterite is thought to be the TL phosphor (Craig and Sears, Forthcoming) and forsterite-bearing chondrules (Sears et al. 1995a). We think it is highly significant that the micrometeorites plot in a field discrete from the ordinary chondrites yet in the same general region as these other forsterite samples and this suggests that the mineral responsible for the TL of the micrometeorites is forsterite.

Forsterite appears to be a common component in many primitive solar system materials, being observed in low petrographic type meteorites, especially in chondrules, (McSween 1977; Olsen and Grossman 1978; Steele et al. 1985a; Steele 1986; Jones 1992), in astronomical nebulae (Koike et al. 2002), in comet dust tail (Crovisier et al. 1997), in interplanetary dust particles (Kloeck et al. 1989), deep sea spherules (Steele et al. 1985b), and grains from comet Wild 2 returned by the Stardust spacecraft (Zolensky et al. 2006).

The Thermoluminescence of Micrometeorites: Quench Products or Relict Grains?

Micrometeorites CS2, CS3, and CS4 are cosmic spherules and normally assumed to be completely melted. However, complete melting would result in the absence of a TL signal, so the presence of a strong TL signal is also evidence for the presence of unmelted minerals within the spherule.

Relic grains have been reported in micrometeorites, including the types measured here (Genge et al. 2008). The amounts of relict grains are small, but TL sensitivity is related more to the composition and crystal structure of the grains, rather than their amount. (In chondrule mesostasis TL is being detected from 1 part in 10^5 of the sample, for instance). We do not believe that fine dendrites produced by quench processes produce significant thermoluminescence because most cosmic spherules do not have measurable TL. In a recent survey, only four out of seventeen micrometeorites—processed in the manner of the present samples—had detectable induced TL, even though their physical and compositional properties were similar to those discussed here and they consisted predominantly of quenched glass. Secondly, while there have been no specific studies of the TL properties meteorite fusion crusts, measurements made close to the crust, and therefore include crust, demonstrate that the level of induced TL in fusion crust material is essentially zero (Vaz and Sears 1977; Akridge et al. 2000). Meteorite fusion crusts are also produced by atmospheric melting and subsequently quenched on the same timescale as micrometeorites. We are therefore confident that the TL we observe in the present spherules is due to relict grains.

The Effects of Atmospheric Heating

Our heating experiments enable us to further address the issue of whether the TL we are detecting is due to quench crystals or relict grains. During atmospheric passage, minerals can dehydrate and oxidize. Elements can be lost by volatilization. Amorphous phases could crystallize, although the time scales for alteration are small. Theoretical studies indicate that small bodies (e.g., <50 µm) can pass through the atmosphere unscathed because they can radiate faster than they absorb energy. Larger grains may suffer a degree of alteration and even partial or complete melting depending on velocity and entry angle. Our heating experiments were performed to provide us with an indication of possible effects of atmospheric passage on the micrometeorite TL properties.

We first considered the possibility of the heat of atmospheric passage dehydrating and crystallizing the materials in the micrometeorite, and thereby creating luminescent phosphors. Figure 3a shows that a CM chondrite heated for thirty seconds in the laboratory at temperatures of 200–1180 °C was not able to cause the formation of TL phosphors. Higher temperatures would cause partial—and eventually complete—melting, which would destroy phosphors. Thus we think it highly unlikely that the TL properties of our micrometeorites were caused by the formation of phosphors during atmospheric heating. But what about altering the TL properties of phosphors originally present in the micrometeorites?

Jilin is an equilibrated ordinary chondrite with very high levels of induced TL. Heating Jilin for 30 s at temperatures up to ~800 °C had little or no influence on the induced TL properties. However, and as discussed above, the phosphor in equilibrated ordinary is feldspar and as the melting point for the feldspar is approached (~1110 °C), we see a complete loss of TL signal. Once melted, the feldspar becomes a glass and glasses do not produce TL. Neither did these glasses crystallize during cooling to produce crystals with measurable TL.

To summarize, heating a meteorite with no initial TL does not cause a TL signal to appear, but heating a sample with a TL signal destroys it at ~1000 °C (where the phosphor is feldspar). Our heating experiments thus suggest that TL properties should not be affected by atmospheric passage unless the phosphors are completely destroyed by melting. Feldspars are melted at relatively low temperatures, but if—as we have suggested—the major phosphor we are seeing in these micrometeorites is forsterite, then significantly higher temperatures are required (~1600 °C) and the likelihood of their TL properties being altered by melting is accordingly reduced.

Measuring the TL Properties of Small Particles

The present measurements were made on equipment essentially unaltered from the equipment used for many years on macrosamples (4 mg powders). It is therefore extremely encouraging that we were able to make the present measurements well above the detection limits of the apparatus. A number of modifications to the apparatus and our procedures would improve our detection limits and enable us to detect TL from smaller or less luminescent particles. First, mechanical changes can be made to the apparatus to bring the sample closer to the detector. Second, focusing optics can be incorporated into the apparatus. Third, heating rates can be increased. Fourth, the samples can be broken open to reveal interior minerals that have not been exposed to atmospheric alteration or terrestrial weathering.

CONCLUSIONS

Four micrometeorites (three cosmic spherules and one scoriaceous irregular object) have relatively high levels of induced TL (comparable with bulk samples of type 3.2–3.4 ordinary chondrites), while thirteen objects had no detectable signal when measured in the same manner. To a first approximation these four micrometeorites have similar TL properties to each other but which distinguish them from CI, most CM, CO, CV, and ordinary chondrites and resemble only the anomalous MAC 87300 CM-like chondrite. We thus suggest that there is no simple linkage between these objects and the major chondrite classes but there might be a linkage with CM-like meteorites. Based on their unusual TL properties and similarities to terrestrial forsterites, and other forsterite-rich extraterrestrial materials, we suggest that an important component of these micrometeorites is forsterite. Heating experiments suggest that atmospheric passage should not have significantly affected the TL properties of these samples, although it is possible that the lower melting point minerals may have melted in the spherules, but not in the scoriaceous particle.

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