THE ASTROPHYSICAL JOURNAL, 514:L125–L127, 1999 April 1

SODIUM TAILS OF COMETS: Na/O AND Na/Si ABUNDANCES IN INTERPLANETARY DUST PARTICLES

FRANS J. M. RIETMEIJER
Institute of Meteoritics, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131; fransjmr@unm.edu
Received 1998 December 21; accepted 1999 February 1; published 1999 February 24

ABSTRACT

The average measured $\mathrm{Na/O} = 2.7 \times 10^{-2}$ (atomic ratio) in chondritic interplanetary dust particles (IDPs) is an order of magnitude higher than the cosmic abundance, and $\mathrm{Na/Si} = 0.11$ is about twice the cosmic value. These ratios are similar to those measured in the mixed and silicate dust particles ejected from the nucleus of comet Halley. The observations indicate that dust in a comet nucleus is the main repository of sodium and that cometary ices are mostly Na free. The measured Na/O value in Hale-Bopp's sodium tail is much less than 0.1 times the cosmic abundance, which is lower than the sodium abundance measured in cluster IDPs collected in the Earth's lower stratosphere.

Subject headings: comets: general — comets: individual (Hale-Bopp 1995 O1) — meteors, meteoroids — solar system: general — Sun: abundances

1. INTRODUCTION

The observations of comet Hale-Bopp's sodium tail showed that the amount of sodium causing this tail is less than ∼0.1% of its cosmic abundance (Cremonese et al. 1997; Kupperman et al. 1998). By comparison, the dust measured in comet Halley, $\mathrm{Na/O} = 1.1 \times 10^{-2}$, was ∼5 times the cosmic abundance (Table 1; Jessberger, Christoforidis, & Kissel 1988). A note of caution should be that this conclusion is based on the assumption that sodium in this comet, and generally in comets, occurs with a cosmic abundance, viz., $\mathrm{Na/O} = 2.4 \times 10^{-3}$ (Anders & Grevesse 1989). A possible source for sodium could be NaOH molecules in ice of the comet nucleus (Combi, DiSanti, & Fink 1997). The sodium tail of comet Hale-Bopp was successfully modeled assuming a point source at the nucleus or in the inner coma. The result suggests that the majority of sodium is still present in ice of the nucleus and/or the embedded dust (Kupperman et al. 1998). The former implies a fractionation process that concentrates sodium in the remaining ice during sublimation that seems difficult to achieve. Wilson, Baumgardner, & Mendillo (1998) concluded that this sodium tail resulted from the evaporation of small dust grains that were released from Hale-Bopp's nucleus. In this Letter, I accept that embedded dust in comet nuclei is the main repository of sodium. This Letter will summarize the available data on chondritic interplanetary dust particles (IDPs) based on a recent review of the mineralogical and petrological properties of these particles collected from the Earth's lower stratosphere (Rietmeijer 1998a).

2. CHONDRITIC AGGREGATE IDPs

The three chemically distinct types of dust ejected from the nucleus of comet P/Halley (Fomenkova et al. 1992) also occur as principal components (PCs) in fine-grained aggregate IDPs, 5–20 μm in diameter (Table 1). These IDPs are part of an accretion hierarchy that began with formation of micron-sized matrix aggregates of variable amounts of these PCs. These aggregates and micron-sized Mg-Fe silicates and Fe-Ni sulfides accreted to form chondritic aggregate IDPs. In turn, they accreted together with ∼10 μm sized Mg-Fe silicates, Fe-Ni sulfides, and magnetite grains to form cluster IDPs greater than 60 μm in diameter (Rietmeijer 1998a, 1998b). The PCs, including spherical units of glass with embedded metals and sulfides (see Bradley 1994), are believed to be the survivors of the presolar and solar nebula dust that was present 4.56 Gyr ago during the accretion in the solar system. Aggregate IDPs also contain amorphous Ca-bearing aluminosilica grains and rare plagioclase ($\mathrm{NaAlSi_3O_8}$-$\mathrm{CaAl_2Si_2O_8}$), alkali-feldspar [$\mathrm{(Na,K)AlSi_3O_8}$], and layer silicate grains (0.4×0.2 to 1.5×1.5 μm in size). These minerals are the only Na-bearing phases found to date in chondritic aggregate IDPs. The time-of-flight mass spectrometer, measurements on board the *VEGA-2* satellite suggest that Na-bearing layer silicate grains ∼0.1–0.5 μm in size were ejected from comet P/Halley's nucleus (Rietmeijer et al. 1989).

All IDPs when they decelerate in the Earth's atmosphere between 100 and 80 km altitude will experience flash heating (5–15 s) whereby IDPs can reach a temperature between 300°C and 1100°C. This particular event can cause substantial thermal modification in particles that otherwise do not show outward signs of melting (Rietmeijer 1998a). Among other things, this thermal spike causes the loss of volatile elements such as sulfur. The exact nature thermal alteration remains obscure as yet, but it certainly is a fruitful area for future research. Sodium is a volatile element that survived flash heating of plagioclase, alkali-feldspar, and layer silicate minerals in aggregate IDPs. It can not be ascertained whether the observed amount of sodium (Table 1) represents the original (preentry) abundance or whether it was affected by evaporative Na loss. Also unknown is whether Na-bearing phases with low boiling points, which might be common to all chondritic aggregate IDPs, are invariably lost during flash heating. In any event, the measured sodium abundances for the IDPs represent lower limits (Table 1).

Upon deceleration in the upper atmosphere, IDPs settle gently at cm $\mathrm{s^{-1}}$ to the collection altitude just above the tropopause. During stratospheric residence (days to weeks) stratospheric gases, condensed aerosols, and noncondensable dust contaminate the IDPs (Rietmeijer 1998a). This type of contamination poses a tremendous analytical challenge for studies of these very small IDPs. It has been documented only for the most obvious cases, e.g., condensed Na-bearing Cl- and Br-rich aerosol particles. It is also a formidable experimental task. The stratospheric aerosol abundances and compositions vary as a function of time, with enhanced abundances possible after a major volcanic eruption with ejecta plumes that penetrated the

TABLE 1

Na/O and Na/Si Abundances Measured in Extraterrestrial Materials and the Solar Photosphere and the Cosmic Values

Sources	Na/O (atomic ratio)	Na/Si (atomic ratio)	Remarks	References
Cosmic value	2.4×10^{-3}	5.74×10^{-2}	Solar nebula (bulk) composition	1
Solar photosphere	1.9×10^{-3}	5.2×10^{-2}	Solar system bulk composition	2
Orgueil meteorite	7.7×10^{-3}	5.6×10^{-2}	Average “refractory” solar system bulk composition modified by parent body processes	1
Chondritic IDPs	2.5×10^{-2}	1.0×10^{-1}	Average composition of accreted anhydrous “refractory” dust not altered on a parent body	3
Chondritic IDPs	1.25×10^{-2}	5×10^{-2}	Average composition of accreted anhydrous “refractory” dust not altered on a parent body	4
Chondritic fragments in a cluster IDP	$4.3(\pm 0.7) \times 10^{-2}$, range: $(3.2\text{–}4.9) \times 10^{-2}$	$1.8(\pm 0.5) \times 10^{-1}$, range: $(1.1\text{–}2.3) \times 10^{-1}$	Average composition of accreted anhydrous “refractory” dust not altered on a parent body; the best documented fragments 17, 18, 116, 24, 25, 28, 312, 51, and 52 from cluster IDP L2008#5 were selected for this Letter	5
Halley dust	1.1×10^{-2}	5.4×10^{-2}	Average composition of the “refractory” mixed and silicate dust	6
Carbonaceous PCs	Not observed	Not observed	These CHON dust analogs of chondritic aggregate IDPs are 400–4000 nm in diameter. Often modified during atmospheric entry flash heating	7, 8
Carbon-bearing, ferromagnesiosilica PCs	Not observed	Not observed	These “mixed” dust analogs in chondritic aggregate IDPs ~100 nm in size have 2 to ~50 nm sized Fe-Mg olivine and Fe-Mg pyroxene, Fe-Ni sulfide, iron oxide, in a refractory hydrocarbon and amorphous carbon matrix.	7, 8
Ferromagnesiosilica PCs	Not observed	Not observed	These “silicate” dust analogs in chondritic aggregate IDPs are mostly 125–1000 nm, up to 1140 nm, in diameter. They are ultrafine- (<50 nm) and coarse-grained (10–410 nm) units with Mg-Fe olivine and Mg-Fe pyroxene, Fe-Ni sulfide, magnetite, and metal (kamacite) in an amorphous matrix and associated amorphous Al-bearing silica material ±Ca.	7, 8
Beta Taurids	No data	9.1×10^{-2} to 0.12	Mesospheric *ion* abundance in a meteor stream associated with comet Encke	9
Perseids	No data	8.0×10^{-1}	Mesospheric *ion* abundance in the meteor shower associated with 1862 III comet Swift-Tuttle	10
Fireball EN151068	No data	4.6×10^{-2}		11
Alkali-feldspars	No data available	$(1.4 \pm 1.3) \times 10^{-1}$	Grains in chondritic aggregate IDP; range: 4.6×10^{-2} to 4.0×10^{-1}	7
Layer silicates	No data available	$(7.0 \pm 5.0) \times 10^{-2}$	Grains in chondritic aggregate IDP; range: 1.5×10^{-2} to 1.3×10^{-1}	7

References.—(1) Anders & Grevesse 1989; (2) Ross & Aller 1976; (3) Thomas et al. 1993; (4) Schramm, Brownlee, & Wheelock 1989; (5) Thomas et al. 1995; (6) Jessberger et al. 1988; (7) Rietmeijer 1998a; (8) Rietmeijer 1998b; (9) Goldberg & Aiken 1973; (10) Herrmann et al. 1978; (11) Borovicka 1993.

tropopause. Ideally, each collection of IDPs should be accompanied by a sampling of stratospheric aerosols. This is not done, and we need to explore other, ad hoc, possibilities to evaluate the extent of IDP contamination.

Cluster IDPs may offer such an opportunity. The cluster IDP L2008#5 included chondritic aggregates, Mg-Fe-Ca silicates, Fe-Ni sulfides, and magnetite fragments (Thomas et al. 1995). Sodium has no cosmochemical affinity for sulfides and Fe oxides. Thus, in the worst-case scenario, its abundances in these fragments could be entirely due to stratospheric aerosol contamination. I selected the four, best documented, fragments from this cluster (Table 2) to explore this thesis. The surface area and their Na/O and Na/Si ratios show a linear correlation that could be an approximation of the contaminant amounts of sodium that occurred during stratospheric settling of this particular cluster IDP. The fragments in Table 2 have an average surface area of 774 μm^2 that compares with 396 μm^2 for its chondritic fragments (Table 1). The surface area is calculated assuming the particles are closed spheres, which is incorrect for the aggregates that have a large surface area. It is not clear that contaminant aerosols will be able to penetrate the pore spaces of these particles. I submit that during settling of this cluster IDP, sodium aerosol contamination was negligible. This cluster IDP contained additional Fe-Ni sulfide and Fe-oxide fragments with variable sodium content. Their silicon content and Na/O define a linear correlation line ($r^2 = 0.8$) that is also the location of the average chondritic aggregate composition, Si = 0.5; Na/O = $4.3(\pm 0.7) \times 10^{-2}$ (Table 1). This result is consistent with observations that small amounts of chondritic

TABLE 2

Na/O and Na/Si (Atomic Ratio) for Selected Fe-Ni Sulfide and Magnetite Fragments in Cluster IDP L2008#5 and Their Surface Area

Fragments	Surface Area (μm^2)	Na/O	Na/Si
Fe-Ni Sulfide			
22	134	4.6×10^{-3}	0.14
38	302	2.2×10^{-2}	0.20
Magnetite			
112	255	3.7×10^{-2}	0.33
21	340	7.6×10^{-2}	0.49

Note.—From Thomas et al. 1995.

aggregate material can be adhered to unmelted silicate and sulfide IDPs (Rietmeijer 1998a).

3. CONCLUSIONS

The average measured sodium abundance in chondritic aggregate IDPs, Na/O = 2.7×10^{-2} and Na/Si = 0.11 (atomic ratios), is similar to the mixed and silicate dust from comet P/Halley and an order of magnitude higher than the cosmic abundance. Thus, Na/O in the sodium tail of comet Hale-Bopp is actually much less than 0.1 times the cosmic abundance. The community that analyzes extraterrestrial materials prefers to normalize measured element abundances to silicon. The Na/Si ratios (Table 1) are also remarkably consistent albeit that the cosmic, solar photosphere, and the Orgeuil meteorite ratios are ∼0.5 times the Na/Si ratio in the mesosphere, chondritic aggregate IDPs, and comet P/Halley dust. This result indicates that dust embedded in the ice of the nucleus is indeed the main repository of sodium. Its amount in cometary dust exceeds the cosmic abundance. Cometary ice is mostly Na free, which matches the observed sodium tail abundances.

This work was supported by NASA grant NAG5-4441.

REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197

Borovicka, J. 1993, A&A, 279, 627

Bradley, J. P. 1994, Science, 265, 925

Combi, M. R., DiSanti, M. A., & Fink, U. 1997, Icarus, 130, 336

Cremonese, G., et al. 1997, ApJ, 490, L199

Fomenkova, M. N., Kerridge, J. F., Marti, K., & McFadden, L.-A. 1992, Science, 258, 266

Goldberg, R. A., & Aiken, A. C. 1973, Science, 180, 294

Herrmann, U., Eberhardt, P., Hidalgo, M. A., Kopp, E., & Smith, L. G. 1978, Space Res., 18, 249

Jessberger, E. K., Christoforidis, A., & Kissel, J. 1988, Nature, 332, 691

Kupperman, D. G., Paxton, L. J., Carbary, J., Romick, G. J., & Anderson, D. E. 1998, Geophys. Res. Lett., 23, 3261

Rietmeijer, F. J. M. 1998a, in Reviews in Mineralogy, Vol. 36, Planetary Materials, ed. J. J. Papike (Washington: Mineralogical Society of America), chap. 2

Rietmeijer, F. J. M. 1998b, in Advanced Mineralogy, Vol. 3, ed. A. S. Marfunin (Berlin: Springer), 22

Rietmeijer, F. J. M., Mukhin, L. M., Fomenkova, M. N., & Evlanov, E. N. 1989, in Lunar and Planetary Science XX (Houston: Lunar and Planetary Institute), 904

Ross, J. E., & Aller, L. H. 1976, Science, 191, 1223

Schramm, L. S., Brownlee, D. E., & Wheelock, M. M. 1989, Meteoritics, 24, 99

Thomas, K. L., et al. 1995, Geochim. Cosmochim. Acta, 59, 2797

Thomas, K. L., Blanford, G. E., Keller, L. P., Klöck, W., & McKay, D. S. 1993, Geochim. Cosmochim. Acta, 57, 1551

Wilson, J. K., Baumgardner, J., & Mendillo, M. 1998, Geophys. Res. Lett., 25, 225