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Aqueous alteration on main belt primitive asteroids: Results from visible spectroscopy ☆

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ABSTRACT

This work focuses on the study of the aqueous alteration process which acted in the main belt and produced hydrated minerals on the altered asteroids. Hydrated minerals have been found mainly on Mars surface, on main belt primitive asteroids and possibly also on few TNOs. These materials have been produced by hydration of pristine anhydrous silicates during the aqueous alteration process, that, to be active, needed the presence of liquid water under low temperature conditions (below 320 K) to chemically alter the minerals. The aqueous alteration is particularly important for unraveling the processes occurring during the earliest times of the Solar System history, as it can give information both on the asteroids thermal evolution and on the localization of water sources in the asteroid belt.

To investigate this process, we present reflected light spectral observations in the visible region (0.4–0.94 μm) of 80 asteroids belonging to the primitive classes C (prevalently), G, F, B and P, following the Tholen (Tholen, D.J. [1984]. Ph.D. Dissertation, University of Arizona, Tucson). classification scheme. We find that about 65% of the C-type and all the G-type asteroids investigated reveal features suggesting the presence of hydrous materials, mainly a band centered around 0.7 μm, while we do not find evidence of hydrated materials in the other low albedo asteroids (B, F, and P) investigated.

We combine the present observations with the visible spectra of asteroids available in the literature for a total of 600 primitive main belt asteroids. We analyze all these spectra in a similar way to characterize the absorption band parameters (band center, depth and width) and spectral slope, and to look for possible correlations between the aqueous alteration process and the asteroids taxonomic classes, orbital elements, heliocentric distances, albedo and sizes. Our analysis shows that the aqueous alteration sequence starts from the P-type objects, practically unaltered, and increases through the P → F → B → C → G asteroids, these last being widely aqueous altered, strengthening thus the results previously obtained by Vilas (Vilas, F. [1994]. Icarus 111, 456–467). Around 50% of the observed C-type asteroids show absorption feature in the visible range due to hydrated silicates, implying that more than ~ 70% of them will have a 3 μm absorption band and thus hydrated minerals on their surfaces, based on correlations between those two absorptions (Howell, E.S. et al. [2011]. EPSC-DPS Joint Meeting 2011, vol. 6. Abstracts, 637).

We find that the aqueous alteration process dominates in primitive asteroids located between 2.3 and 3.1 AU, that is at smaller heliocentric distances than previously suggested by Vilas et al. (Vilas, F., Hatch, E.C., Larson, S.M., Sawyer, S.R., Gaffey, M.J. [1993]. Icarus 102, 225–231). The percentage of hydrated asteroids is strongly correlated with their size. The aqueous alteration process is less effective for bodies smaller than 50 km, while it dominates in the 50–240 km sized primitive asteroids.

No correlation is found between the aqueous alteration process and the asteroids albedo or orbital elements. Comparing the ~ 0.7 μm band parameters of hydrated silicates and CM2 carbonaceous chondrites, the meteorites that have aqueous altered asteroids as parent bodies, we see that the band center of meteorites is at longer wavelengths than that of asteroids. This difference on center positions may be attributed to different minerals abundances, and to the fact that CM2 available on Earth might not be representative of the whole aqueous altered asteroids population.

☆ Based on observations carried out at the European Southern Observatory (ESO), La Silla, Chile, ESO proposals 062.S-0173 and 064.S-0205 (PI M. Lazzarin).

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1. Introduction

The distribution of the asteroids taxonomic classes follows a radial structure varying with the heliocentric distance: the inner and middle belt is dominated by differentiated bright asteroids (M, E, V, and prevalently S-types) that have experienced high temperatures in the past and that are constituted by volatile-poor silicates and metals, while dark primitive asteroids (B, P, D, and prevalently C-types), rich in carbonaceous chondrite-like materials and formed in a colder environment, dominate the outer belt to the Jupiter Trojans. This asteroid class distribution corresponds to a radial variation of the formation temperatures and to the presence of different mineralogical materials with increasing heliocentric distance. These materials have also been partially mixed in the past due to dynamical interaction of asteroids with each others and with planets, and altered over time by different processes such as collisions, aqueous alteration, and space weathering.

The aqueous alteration process acts on primitive asteroids (C, G, B, F and P-types, following the Tholen (1984) classification scheme) located mainly between 2.6 and 3.5 AU, in the so called zone of aqueous alteration (Vilas, 1994; Fornasier et al., 1999). The aqueous alteration process produces the low temperature (<320 K) chemical alteration of materials by liquid water which acts as a solvent and produces hydrated minerals such as phyllosilicates, sulfates, oxides, carbonates, and hydroxides. This means that liquid water was present in the primordial asteroids, produced by the melting of water ice by heating sources, very probably by ^{26}Al decay.

Reflectance spectroscopy of aqueous altered asteroids shows absorption features in the 0.6–0.9 and 2.5–3.5 μm regions, which are diagnostic of, or associated with, hydrated minerals. The most prominent and unambiguous indicator of hydration is the 3 μm band (Lebofsky, 1980; Jones et al., 1990; Rivkin et al., 2002; Vilas, 1994, 2005; Howell et al., 2011; Takir and Emery, 2012), associated with *free* water molecules, and to OH ion bounded in the mineral crystal lattice; while in the visible range there are several bands, centered around 0.43 μm, 0.60–0.65 μm, 0.70 μm and 0.80–0.90 μm, attributed to charge transfer transitions in oxidized iron (Vilas et al., 1993, 1994; Vilas, 1994; Barucci et al., 1998; Fornasier et al., 1999).

The study of aqueous alteration is particularly important for unraveling the processes occurring during the earliest times in Solar System history, as it can give information both on the thermal processes and on the localization of water sources in the asteroid belt, and for the associated astrobiological implications. Indeed it has been suggested (Morbidelli et al., 2000; Lunine, 2006) that the Earth current supply of water was delivered mostly by asteroids, not comets, some time following the collision that produced the Moon (which would have vaporized any of the water existing at that time). While asteroids and comets from the Jupiter–Saturn region were deemed to be the first water deliverers (when the Earth was half its size), the bulk of the water delivered was found to originate from a few planetary embryos, originally formed in the outer asteroid belt and accreted by the Earth at the final stage of its formation. Morbidelli et al. (2000) found that the measured amount of the D/H ratio in the water on Earth correlates very well with the ratio of D/H typical of water condensed in the outer asteroid belt. Alexander et al. (2012), analyzing the bulk hydrogen and nitrogen isotopic compositions of CI chondrites, suggest that these meteorites were the principal source of Earth volatiles, while the D/H of all comets except Hartley 2 (Hartogh et al., 2012) are quite different from the Earth oceans value.

The snow line has been located within or nearby the asteroid belt (Lunine, 2006; Cyr et al., 1998), and, following the recent nebular kinetics models results, it may have migrated as the nebula evolved, sweeping across the entire asteroid belt (Dodson-Robinson et al., 2009). According to the latest dynamical models, it has also been suggested that part of the main belt primitive asteroids were formed either between the giant planets or in the trans-neptunian region (Walsh et al., 2011), and then injected into the inner Solar System.

Water ice has been tentatively identified on the surfaces of the outer primitive asteroids Themis and Cybele (Rivkin and Emery, 2010; Campins, 2010; Licandro, 2011), and some main belt asteroids, originated from the Themis family (Hsieh and Jewitt, 2006; Hsieh et al., 2009, 2012), were discovered to become active (they are also called main belt comets).

The fact that primitive asteroids had retained water ice in the past and may have enriched the Earth of water and possibly organic material, favoring the appearance of life on our planet, is of great interest for the scientific community. Indeed all of the major space agencies are planning sample return missions to primitive near Earth objects (NEO): NASA will launch OSIRIS-REx in 2016 to sample the Asteroid (101955) Bennu, JAXA will launch Hayabusa-2 in 2014 to bring back material from (162173) 1999 JU3, and the mission MarcoPolo-R has been proposed to the European Space Agency (ESA) in the framework of the Cosmic Vision 2015-2025 program, for a sample return from (342843) 2008 EV5.

Some evidence of hydrated material has been found also in the outer Solar System, with the detection of peculiar absorption bands on the spectra of some TNOs that could be possibly associated with the aqueous alteration process (Fornasier et al., 2004a, 2009; Lazzarin et al., 2003; De Bergh et al., 2004; Alvarez-Candal et al., 2008).

In this work we focus on spectroscopy in the visible region of low albedo asteroids. We present new visible spectra for 80 objects belonging to the C-complex and localized between 2.3 and 4.0 AU, with the aim to investigate the aqueous alteration process that has involved the C, B, F, P, and G primitive classes. To do so, we have studied a larger sample including visible spectra from the literature for a total of 600 primitive main belt asteroids. We have analyzed all these data to spectrally characterize the bands associated with the aqueous alteration process in the visible region (mainly the one centered around 0.7 μm), and look for the relationships between this process and the heliocentric distance, albedo and diameter of the investigated objects. We have also compared the spectral parameters associated with the 0.7 μm band for asteroids and for the CM2 carbonaceous chondrites, which show evidence of aqueous altered materials on their surface and in particular they show the 0.7 μm band in their spectra.

2. Observations and data reduction

The data presented in this work were obtained during 2 runs on March and November 1999 at the 1.52 m telescope of the European Southern Observatory (ESO), in Chile. The telescope was equipped with a Boller & Chivens spectrograph and a Loral Lesser CCD as detector (2048 $\times$ 2048 pixels). The grating used was a 225 g/mm, with a dispersion of 331 Å/mm in the first order, covering the $0.42 < \lambda < 0.93$ μm spectral range. The CCD has a 15 μm square pixels, giving a dispersion of about 5 Å/pixel in the wavelength direction.

Each spectrum was recorded through a slit oriented in the East–West direction. The slit was opened from 2 to 5 arcsec in order to reduce effects due to differential refraction and the possibility of losing signal due to guiding errors of the telescopes.

An order sorting filter cutting the signal below 4200 Å was used to prevent overlapping of the second spectral order on the spectrum.

During each night, we also recorded bias, flat-field, calibration lamp, and solar analog star spectra (Hardorp, 1978) at different intervals throughout the night. The stars were observed at airmasses similar to those of the objects.