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The composition of M-type asteroids: Synthesis of spectroscopic and radar observations

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ABSTRACT

We have conducted a radar-driven observational campaign of 22 main-belt asteroids (MBAs) focused on Bus–DeMeo Xc- and Xk-type objects (Tholen X and M class asteroids) using the Arecibo radar and NASA Infrared Telescope Facilities (IRTF). Sixteen of our targets were near-simultaneously observed with radar and those observations are described in a companion paper (Shepard, M.K., and 19 colleagues [2010]. Icarus, in press). We find that most of the highest metal-content asteroids, as suggested by radar, tend to exhibit silicate absorption features at both 0.9 and 1.9 μm, and the lowest metal-content asteroids tend to exhibit either no bands or only the 0.9 μm band. Eleven of the asteroids were observed at several rotational longitudes in the near-infrared and significant variations in continuum slope were found for nine in the spectral regions 1.1–1.45 μm and 1.6–2.3 μm. We utilized visible wavelength data (Bus, S.J., Binzel, R.P. [2002b]. Icarus 158, 146–177; Fornasier, S., Clark, B.E., Dotto, E., Migliorini, A., Ockert-Bell, M., Barucci, M.A. [2010]. Icarus 210, 655–673.) for a more complete compositional analysis of our targets. Compositional evidence is derived from our target asteroid spectra using two different methods: (1) a χ^2 search for spectral matches in the RELAB database, and (2) parametric comparisons with meteorites. This paper synthesizes the results of the RELAB search and the parametric comparisons with compositional suggestions based on radar observations. We find that for six of the seven asteroids with the highest iron abundances, our spectral results are consistent with the radar evidence (16 Psyche, 216 Kleopatra, 347 Pariana, 758 Mancunia, 779 Nina, and 785 Zwetana). Three of the seven asteroids with the lowest metal abundances, our spectral results are consistent with the radar evidence (21 Lutetia, 135 Hertha, 497 Iva). The remaining seven asteroids (22 Kalliope, 97 Klotho, 110 Lydia, 129 Antigone, 224 Oceana, 678 Fredegundis, and 771 Libera) have ambiguous compositional interpretations when comparing the spectral analogs to the radar analogs. The number of objects with ambiguous results from this multi-wavelength survey using visible, near-infrared, and radar wavelengths indicates that perhaps a third diagnostic wavelength region (such as the mid-infrared around 2–4 μm, the mid-infrared around 10–15 μm, and/or the ultraviolet around 0.2–0.4 μm) should be explored to resolve the discrepancies.

1. Introduction

Main-belt asteroids (MBAs) are critical for testing and modifying formation models of the Solar System. X-complex asteroids (Tholen, 1984; Bus and Binzel, 2002b; Mothé-Diniz et al., 2003) play a fundamental role in the investigations of early formation theories because they represent about 20% of inner main-belt asteroids and because they potentially include asteroid metallic cores (*cf*. Bell et al., 1989).

Measurements in the near-infrared wavelengths (0.8–4.2 μm) are useful for compositional information such as absorption band center positions and depths (indicators of silicate mineralogy), continuum slope (indicator of spectral redness due to optical alteration, organics, or presence of metal) (Chapman and Gaffey, 1979; Clark et al., 2004a,b), and 3-μm features (indicator of hydrated mineral abundances (Rivkin et al., 1995, 2000)).

Recent work in the visible and near-infrared wavelength ranges indicates that the X-complex asteroids are spectrally diverse beyond the sub-groups (E, M, P) suggested by Tholen on the basis of albedo (Clark et al., 2004b). One Tholen X-complex subgroup,

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the M-type asteroids, have moderate albedos ($0.10 \geqslant P_v \geqslant 0.30$) and are spectrally featureless as described by the Tholen taxonomy based on the 8-color ECAS data (Zellner et al., 1985). These objects have been proposed to be the parent bodies of iron meteorites (Gaffey et al., 1979). It is also suggested that enstatite chondrite meteorites and heavily altered carbonaceous chondrites are potential M-type asteroid analogs (Gaffey et al., 1979; Vilas, 1994) due to weak absorptions at 0.7 and 0.9 μm.

In this paper, we present updated results from our long-term survey of the X-complex asteroids. We initially began this work in 2003, targeting the Tholen M-types (Tholen, 1984; Tholen and Barucci, 1989). Since that time, taxonomy has evolved and our targets have been newly classified according to the Bus–DeMeo system (DeMeo et al., 2009). The Bus–DeMeo taxonomy builds on the Bus taxonomy (Bus, 1999; Bus and Binzel, 2002a,b; DeMeo et al., 2009) by using both visible and infrared data to group asteroids spectrally from 0.4 to 2.5 μm according to principal components. In the Bus–DeMeo system, our targets are now called Xc- and Xk-types, however some of them are designated Xe or X-types. No matter what they are called taxonomically, these asteroids are noted for their lack of strong spectral features, and their near-infrared slopes range widely from flat to red. This paper presents new observations, several methods of data analysis, and a synthesis of all work we have conducted to date. This paper directly follows and builds on our previous results (Shepard et al., 2008b, 2010; Ockert-Bell et al., 2008).

2. Observations and data reduction

Our observations were conducted at the Mauna Kea Observatory 3.0 m NASA Infrared Telescope Facility (IRTF) in Hawaii. We used the SpeX instrument, equipped with a cooled grating and an InSb array (1024 × 1024) spectrograph at wavelengths from 0.82 to 2.49 μm (Rayner et al., 2003). Spectra were recorded with a slit oriented in the north–south direction and opened to 0.8 arcsec. A dichroic turret that reduces the signal below 0.8 μm was used for all observations.

Table 1 gives a summary of the asteroids that were observed in the near-infrared and radar for this program and Table 2 gives the observing circumstances. Following normal data reduction procedures of flat fielding, sky subtraction, spectrum extraction, and wavelength calibration, each spectrum was fitted with the ATRAN atmospheric model for telluric absorption features (Lord, 1992; Bus et al., 2003; Sunshine et al., 2004). This procedure required an initial estimate of precipitable water in the atmospheric optical path using the zenith angle for the observation and the known τ-values (average atmospheric water) for Mauna Kea. This initial guess was iterated until the best fit between predicted and observed telluric band shapes was obtained, and an atmospheric model spectrum was generated (Bus et al., 2003). Following this, each asteroid spectrum was divided by the atmospheric model and then ratioed to each star spectrum, similarly reduced, before normalization at 1.2 μm. The final spectra we report are averages of 3–5 asteroid/star ratios, calculated to average out variations due to standard star and sky variability.

Usually, 2–5 different standard stars were observed on any given night at the telescope (64 Hyades, or any of 9 Landolt stars). We used only solar standard stars. In addition, 1–3 observations were obtained of each different standard star. Although we did not attempt a quality judgment of the asteroid observations, we paid careful attention to the star observations in order to eliminate "bad" spectra and/or "bad" nights at the telescope (such as nights when unresolved stratospheric clouds were too variable to be removed in reduction). As a matter of routine, we calculate the ratios of asteroid/star1 over asteroid/star2 to make sure we find no residual features that are due to bad star measurements (see discussion in Ockert-Bell et al. (2008)).

There are a number of possible causes of observed spectral variations in standard star and asteroid spectra. These include: (1) random fluctuations in detector response (especially at the wavelength extremes near 0.8 and 2.5 μm), (2) unresolved background objects adding light, (3) slit and grating position variations due to imperfect tracking of the telescope, (4) unresolved differences in atmospheric conditions, (5) intrinsic color differences between standard stars, (6) change in phase angle of asteroid observations over long time spans, and (7) rotational compositional variations and/or grain size variations. Continuum slope variations are sensitive to effects (3) and (4), and in particular, effect (4) is a very common and difficult problem to resolve when analyzing data.

Table 1
Asteroids observed (2001–2009) for this study.

Name	Bus–DeMeo type	Tholen type	Family	*a* (AU)	*D* (km)	*P* (h)	Radar albedo
16 Psyche[a]	Xk[b]	M		2.92	186 ± 30	4.196	0.42 ± 0.10
21 Lutetia[a]	Xc[b]	M		2.44	100 ± 11	8.172	0.24 ± 0.07
22 Kalliope	X[b]	M		2.91	162 ± 3	4.148	0.18 ± 0.05
55 Pandora[a]	Xk	M		2.71	67	4.804	–
77 Frigga[a]	Xe	M		2.67	69	9.012	–
97 Klotho	Xc[b]	M		2.67	83 ± 5	35.15	0.26 ± 0.05
110 Lydia[a]	Xk[b]	M	Lydia	2.73	89 ± 9	10.926	0.20 ± 0.12
129 Antigone[a]	Xk	M		2.87	113 ± 12	4.957	0.36 ± 0.09
135 Hertha	Xk	M	Nysa	2.43	77 ± 7	8.401	0.18 ± 0.05
136 Austria[a]	Xc	M		2.29	40	11.5	–
216 Kleopatra[a]	Xe[b]	M		2.8	124 ± 15	5.385	0.60 ± 0.15
224 Oceana[a]	Xc	M		2.65	62 ± 2	9.388	0.25 ± 0.10.
250 Bettina	Xk	M		3.15	80	5.054	–
347 Pariana	Xk	M		2.61	51 ± 5	4.053	0.36 ± 0.09
441 Bathilde[a]	Xc	M		2.81	70	10.447	–
497 Iva	Xk	M		2.86	40 ± 8	4.62	0.24 ± 0.08
678 Fredegundis	Xk	X		2.57	42 ± 4	11.62	0.18 ± 0.05
758 Mancunia[a]	Xk	X		3.19	85 ± 7	12.738	0.55 ± 0.14
771 Libera	Xk	X		2.65	29 ± 2	5.892	0.17 ± 0.04
779 Nina	Xk			2.67	77 ± 2	11.186	0.26 ± 0.24
785 Zwetana[a]	Cb[b]	M		2.57	49 ± 2	8.918	0.33 ± 0.08
872 Holda[a]	Xk	M		2.73	30	7.2	–

a is the semi-major axis of the asteroid, *D* is the asteroid diameter, *P* is the rotation rate. Most values retrieved from the JPL Horizons database, http://ssd.jpl.nasa.gov (January, 2008). Diameter and radar albedo with error bars are from Shepard et al. (2010).

[a] Asteroids that were published in Ockert-Bell et al. (2008). Bus–DeMeo taxonomy from DeMeo et al. (2009).

[b] Retrieved from http://smass.mit.edu/busdemeoclass.html (March, 2009).