OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term⋆

Search for a Differentiated Asteroid Family

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Abstract of Scientific Justification

Dynamical asteroid families resulting from catastrophic disruptions represent the interiors of their former parent bodies. Differentiation of a large initially chondritic parent body is expected to produce an "onion shell" object with a metal core, a thick olivine-rich mantle, and a thin basaltic crust. However, instead of the mineralogical diversity expected from the disruption of a differentiated parent body, most asteroid families tend to show similar spectra among the members. Moreover, spectra of metal-like materials and olivine-dominated assemblages have not been detected in asteroid families in the Main Belt and the expected mantle material is missing from the meteorite record. The deficit of olivine-rich mantle material in the meteorite record and in asteroid observations is known as the "Missing Mantle" problem. For years the best explanation for the lack of mantle material has been the "battered to bits" hypothesis that states that all differentiated parent bodies (aside from Vesta) were disrupted very early in the solar system and the resulting olivine-rich material was collisionally broken down until the object diameters fell below our observational limits. However, in a new, competing hypothesis, Elkins-Tanton et al. (2013) has suggested that previous work has overestimated the amount of olivine produced by the differentiation of a chondritic parent body. *We propose to obtain near-infrared spectra of asteroids within the Massalia, Merxia, and Agnia S-type families to search for compositional variations within the families that are indicators of partial or full differentiation and to quantitatively constrain the two competing "Missing Mantle" hypotheses. This proposal requests 2 nights on MAG1 FIRE from UAO during the 2015A semester.*

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MAG1	f/11	FIRE			2	bright	Apr-Jul	Jan-Jul	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: This proposal requests 2 nights on MAG1 FIRE from UAO. We have targets throughout the semester, but available objects are concentrated in April-July.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	10023	11:58:31.6	+02:49:19.9	Massalia, V=17.7
2	12891	12:11:57.5	-01:53:50.8	Agnia, V=17.6
3	14928	12:22:20.2	+01:30:46.5	Massalia, V=17.9
4	9424	12:50:39.1	-01:17:10.8	Massalia, V=17.9
5	13742	14:21:29.9	-06:03:24.9	Merxia, V=18.7
6	17292	14:39:14.4	-16:53:41.7	Agnia, V=17.8
7	13723	14:46:57.6	-15:42.22.0	Merxia, V=18.4
8	15458	14:47:49.2	-13:57:56.7	Massalia, V=18.3
9	15217	15:31:15.5	-15:16:15.0	Massalia, V=18.1
10	25131	15:42:52.6	-14:12:28.1	Merxia, V=18.2
11	8120	15:56:58.7	-16:45:39.9	Massalia, V=17.4
12	23874	16:04:51.1	-14:06:57.6	Agnia, V=17.7
13	25775	16:48:45.8	-13:45:51.7	Merxia, V=17.4
14	14169	17:19:14.4	-25:59:41.8	Merxia, V=17.8
15	25701	17:40:34.8	-15:42:01.3	Merxia, V=18.5
16	9884	18:25:45.1	-26:07:02.4	Massalia, V=18.8
17	47860	19:07:56.3	-30:53:11.1	Merxia, V=17.5
18	48558	19:10:28.7	-27:37:34.6	Merxia, V=18.3
19	26442	19:21:23.3	-30:23:02.0	Merxia, V=17.5
20	9924	19:38:57.2	-24:29:23.8	Agnia, V=17.7
21	75902	20:02:02.8	-16:41:32.2	Merxia, V=18.5
22	7989	21:51:29.5	11:56:14.7	Massalia, V=17.2

Approval for Instrument Use from PI: N/A

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Asteroid families were first identified as clusters of objects in proper orbital element space. It has long been recognized that these dynamical groups were produced by catastrophic collisions or large cratering events that caused fragmentation of the parent body and ejection of asteroidal fragments with velocities sufficient to prevent re-accretion (e.g., Durda et al. 2007, Zappala et al. 1996).

Due to this collisional and often catastrophic formation process, asteroid families should provide us with the opportunity to probe the interiors of the former parent bodies. For chondritic starting compositions, differentiation likely occurred in those objects larger than 20 km in diameter which accreted within $\sim$2.7 Myrs of the condensation of the first Solar System solids (Moskovitz and Gaidos 2011). We expect differentiation to result in an "onion shell" object with an iron-nickel core, a thick olivine-dominated mantle, and a thin plagioclase/pyroxene crust (Fig. 2, Burbine et al. 1996). However, rather than such mineralogical diversity, most asteroid families tend to show similar spectra (and therefore composition) among the members. Most asteroid families have compositions linked to either dark, primitive, potentially carbonaceous materials (C-types) or brighter olivine-pyroxene assemblages (S-types, a subset of which are ordinary chondrite analogs). Figure 1 shows the variety of spectroscopic types seen in the asteroid population. Spectroscopic studies have observed a paucity of metal-like materials and olivine-dominated assemblages in asteroid families in the Main Belt. The lack of observable spectral diversity suggests that the families studied originated either from an undifferentiated (ordinary chondrite-like) parent body (as in the Koronis family, which was shown to contain ordinary chondrite material during the Galileo flyby of (243) Ida (Chapman 1996)) or from a non-catastrophic collision that expelled a relatively small amount of parent body material without exposing the mantle or core (as in the case of (4) Vesta (Marchi et al. 2012)).

However, the dearth of core and mantle material in the Main Belt can not be completely explained by a lack of differentiation and a plethora of non-catastrophic family forming collisions. Evidence from the meteorite record clearly shows that there were numerous catastrophic collisions of differentiated parent bodies in our Solar System. Compositional groupings of iron meteorites provide evidence for at least 60 differentiated parent bodies that were disrupted. However, the corresponding mantle material from these differentiated bodies is not present in the meteorite record. Additionally, geochemical studies of HED (howardite-eucrite-diogenite) meteorites from Vesta suggest that the majority of Vesta, and other similar objects, is comprised of mantle material.

The deficit of olivine-rich mantle material in the meteorite record and in asteroid observations is known as the "Missing Mantle" problem and has been discussed for over twenty-five years (Bell et al. 1989, Burbine et al. 1996). For years the best explanation has been the "battered to bits" hypothesis: that all differentiated parent bodies (aside from Vesta) were disrupted very early in the solar system and the resulting olivine-rich material was collisionally broken down over time until the object diameters fell below our observational limits.

This would suggest that the iron-nickel meteorites are from old families: whatever remains of the core and mantle fragments in the Main Belt has disappeared into the background population. However, in a new competing hypothesis, Elkins-Tanton et al. (2013) have suggested that previous work has overestimated the amount of olivine produced by the differentiation of a chondritic parent body: small bodies do not fractionate effectively enough to produce much olivine before solidification. This would suggest that the "missing" olivine was never there to begin with.

We propose to obtain near-infrared spectra of asteroids in the Massalia, Merxia, and Agnia S-type Main Belt asteroid families. These families were carefully chosen for the proposed spectroscopic survey because based on existing data, they have compositions most closely associated with a history of thermal metamorphism and because they represent a range of collisional formation scenarios. In addition, the relatively young ages (under 400 Myr) of these families permit testing of the "battering to bits" timescale. Each family has a relatively small number of previous spectroscopic observations and most observations have been obtained only in visible wavelengths. The observational campaign proposed here will observe 30-35 objects within each individual family. This sample size will allow adequate sampling of each family at a variety of sizes while remaining feasible within telescope resources.

Many past studies of asteroid families have applied visible wavelength spectroscopy, low-resolution spectrophotometry, and albedos to study the compositions of the asteroid families (e.g., Cellino et al. 2002, Masiero et al. 2011, Mothe-Diniz et al. 2005, Thomas et al. 2012). These methods allow for broad studies of asteroid populations, but can miss the subtleties that allow for a precise study of mineralogy. In the near-infrared wavelength region, the 1- and 2-μm absorption features are diagnostic of the amount of olivine and pyroxene in a body and of the chemistries of the minerals. Near-infrared spectroscopy also enables more definitive taxonomic classification of the relevant A- (olivine-rich potential mantle material), S- (olivine and pyroxene assemblages that represent various levels of thermal metamorphism), and V- (pyroxene-rich crust material) classes. If the families are the products of fully differentiated parent bodies, we can expect a variety of spectral types within each family. Alternatively, some members of the background Main Belt population might be interlopers that were misidentified by the numerical processes that identify members of the asteroid families.

Once each spectrum has been reduced it will be classified and analyzed. The spectra will be classified in the Bus-DeMeo system using the online taxonomic classifier (DeMeo et al. 2009). For objects with large 1-μm and 2-μm absorption features (the S-, Q-, V-, and A-complexes) indicative of crystalline olivine and/or pyroxene, a full analysis of traditional band parameters will be completed. We will calculate the 1-μm Band Depth, 1-μm Band Center, 2-μm Band Center, and Band Area Ratio. Band Centers are determined by calculating the local minimum for an absorption band after a linear continuum has been divided out. Band Area Ratio is defined as the ratio of the area of the 2-μm band to the area of the 1-μm band.

We will also use the Modified Gaussian Model (MGM) to calculate band parameters. MGM is a numerical tool for modeling the component absorption bands in visible and near-infrared spectra (Sunshine et al. 1990). The modified Gaussians that model the spectral shape make MGM a powerful tool for the geometric tasks associated with calculating band parameters, thus enabling a more accurate calculation. The comparison of band parameters calculated using traditional linear continua methods and those calculated using the MGM will permit us to assess the accuracy of traditional band parameter calculations. Component absorption bands and mineralogies will also be derived from the MGM fits.

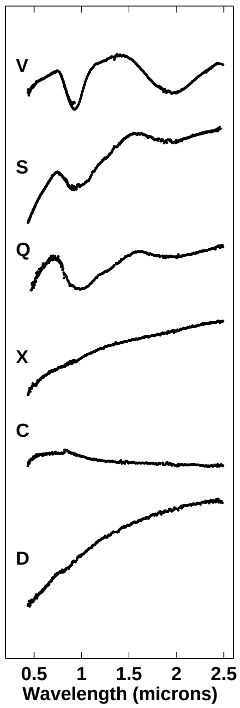
For S-types, the 1-μm Band Center is a function of the relative abundances and compositions of olivine and pyroxene, while the 2-μm Band Center is a function of the pyroxene composition. The Band Area Ratio is a measure of the relative abundances of olivine and pyroxene. For some S- and V-types the band parameters can be used to calculate specific composition values such as olivine/(olivine + pyroxene) and the corresponding olivine and pyroxene chemistries (e.g., Dunn et al. 2010). Given sufficient spectral SNR, mineralogy calculations can be done to a high level of precision.

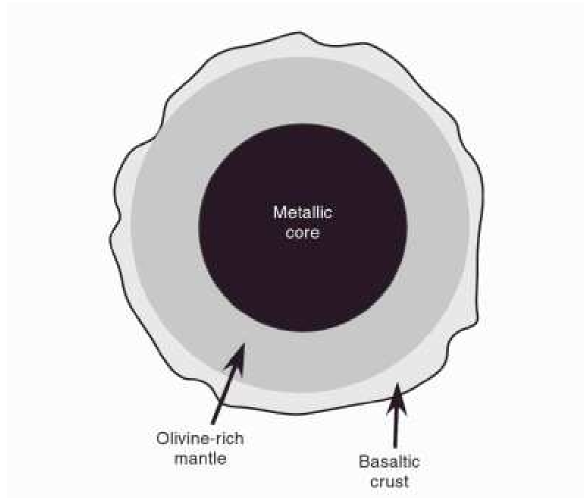
Our spectroscopic survey of the Massalia, Merxia, and Agnia S-type families will search for compositional variations within the families that are indicators of partial or full differentiation. We will determine if any observed family members have mineralogies consistent with "missing mantle" olivine. The presence or absence of mineralogical variation will constrain the "battered to bits" model of collisional evolution and test the hypothesis that previous work has over-estimated the amount of olivine that results from asteroid differentiation.

References:

Bell et al. 1989, *Asteroids II*, 921-945.
Burbine et al. 1996, Meteoritics and Planetary Science, 31, 607-620.
Cellino et al. 2002, *Asteroids III*, 633-643.
Chapman 1996, Meteoritics and Planetary Science, 31, 699-725.
DeMeo et al. 2009, Icarus, 202, 160-180.
Dunn et al. 2010, Icarus, 208, 789-797.
Durda et al. 2007, Icarus, 186, 498-516.
Elkins-Tanton et al. 2013, LPI Contributions 1719, 1351.
Marchi et al. 2012, Science 336, 690.
Masiero et al. 2011, Astrophysical Journal, 741, 68.
Moskovitz and Gaidos 2011, Meteoritics and Planetary Science, 46, 903-918.
Mothe-Diniz et al. 2005, Icarus, 174, 54-80.

Sunshine et al. 1990, Journal of Geophysical Research: Solid Earth, 95, 6955-6966.
Sunshine et al. 2004, Meteoritics and Planetary Science, 39, 1343-1357.
Thomas et al. 2012, Icarus, 219, 505-507.
Zappala et al. 1996, Icarus, 124, 156-180.





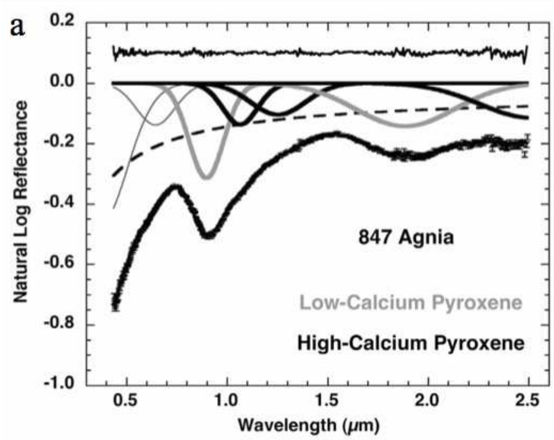


Figure 1: *Left:* Visible and near-infrared spectra of six distinct taxonomic types. This panel shows that spectroscopic types separate due to slope and absorption features in both the visible and near-infrared. The three families that are the focus of this program are S-type. The two broad absorption features enable detailed investigations of their silicate compositions.

Figure 2: *Top Right:* Differentiation is expected to produce interior compositional diversity. For an initially chondritic parent body, models predict an iron-nickel metal core, an olivine mantle, and a thin crust. The resulting structure is often referred to as an "onion shell".

Figure 3: *Bottom Right:* Modified Gaussian Model (MGM) analysis of Agnia. From bottom to top of the panel this model shows the observed spectrum, the dashed line spectral continuum, the modified Gaussians which correspond to mineral absorptions used to fit the spectrum (and therefore identify the mineralogical components), and the residual of the fit to the spectrum. This analysis by Sunshine et al. (2004) demonstrated that the asteroid Agnia showed signs of partial differentiation. We will determine if this is consistent throughout the family.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Our full obeservational campaign will obtain visible and near-infrared spectra for ∼100 objects in the Massalia, Merxia, and Agnia families. Each family has a relatively small number of previous spectroscopic observations and most observations have been obtained only in visible wavelengths. This observational campaign will allow for 30-35 observations within each individual family and will enable a thorough investigation of composition and compositional variation within each family. This sample size will allow adequate sampling of each family at a variety of sizes.

The target lists for the Massalia, Merxia, and Agnia families were chosen to cover a wide range of asteroid diameters and have been carefully constructed to optimize time on our proposed observatories. We determined the semester and hemisphere of peak optical brightness for the targets over a two year period from 2014B to 2016A. By carefully examining our target list, we have maximized the efficiency of our program to minimize the requests for large telescope time and to reduce the demands that our program places on the UAO telescope system.

MAG1 FIRE We plan to use FIRE to gather near-infrared spectra of a subset of our Massalia, Merxia, and Agnia target lists. We used information from the FIRE online observer guide and past experience with the instrument to determine the magnitude range available and the minimum exposure time for SNR∼100. For our program, we plan to use the high-throughout prism (longslit) observing mode which provides spectra from 0.82-2.51 μm in a single exposure. Our program requires a minimum spectral resolution of R∼100. We chose this resolution since we will investigate wide absorption features and previous observations at R∼100 (NASA IRTF SpeX instrument) have yielded precise calculations of the mineralogies of asteroids. The FIRE instrument has variable resolution over the the bandpass (R_J=500, R_H=450, R_K=300). The minimum FIRE resolution exceeds our minimum requirement, so we expect to bin by at least 2 in the wavelength direction. We define a faint observational limit of V=20 and a bright magnitude limit of V=17 for this observing run. Most of the bright (V<17), and therefore large, objects in our target list will have an apparition in the northern hemisphere during our two year survey. We will observe these objects using the low resolution prism mode on the SpeX instrument at the NASA Infrared Telescope Facility (IRTF). This allows us to focus on small, faint objects during our FIRE observations. Our target list has many objects in this magnitude range in the southern hemisphere during 2015A. Past experience suggest on source exposure times of t=15 minutes for V=17-18, t=30 for V=18-19, and V=19-20. We identified the peak optical magnitude that each object will reach during the semester and determined exposure times for these magnitudes. By using the peak optical magnitudes we calculate the minimum time required to observe all the available objects this semester. Using these exposure times and an overhead (slew, setup, readout, on-slit dithers) time equal to 30 minutes for each object we calculate a total object time of 19 hours. Additionally, we anticipate adding 3 solar analog standards per night (40 minutes each). We request 2 nights for this program in 2015A. Our targets are available throughout the entire semester with a larger concentration of available objects in the April to July timeframe. The target list presented shows the objects available in the 2015A semester, their family membership, and their peak optical magnitude.

Since the light observed from each object is reflected solar light, we require a minimum of one observation of a solar analog star for each night. Since additional spectra are optimal we schedule for three each night. We also require spectroscopic flats and spectra of calibration lamps (e.g., Ar) for each night. Every observation should be done in a dither pattern. By changing the location of each spectrum on the detector, we can subtract out the sky signal and optimize signal to noise.

We require the ability to track an object with non sidereal motion.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

1) We were allocated 1.5 nights on MAG1 FIRE for this program in 2014B. This proposal requests 2 nights during 2015A. We anticipate this observing program to be completed in 2 years (2014B-2016A). We will be requesting 1-2 nights per semester for the duration of this period.

We have targets throughout the entire semester, but we have a larger concentration of available objects in the April-July timeframe. We have calculated the observing windows for our objects and they should be observed within these windows because their motion can cause large magnitude variations in relatively short periods of time.

PI Trilling and Co-I Thomas executed a larger spectroscopic observing using UAO facilities in 2010-2011. Our experience and success with that endeavor suggests that we can perform the necessary observations, reductions, and analysis in the timeframe proposed.

2) This program is divided between visible and near-infrared spectrographs in the northern and southern hemispheres. Near-infrared observations for this program will be taken with FIRE and with the SpeX instrument on the NASA Infrared Telescope Facility (IRTF). Complementary visible observations will be taken with Lowell Observatory's DeVeny spectrograph and with Goodman on the SOAR (Southern Astrophysical Research) Telescope.

We have calculated observing windows (with corresponding proposal semesters) and hemispheres where objects with D>2 km from our three asteroid families are brightest. We will observe a representative sample of the Massalia, Merxia, and Agnia families over this wide size range. We do not intend on observing every object on our target list. In order to minimize our requests for large telescope time and reduce the demands that our program places on the UAO telescope system, we focus only on small, faint objects for this proposal to use the 6.5 m Magellan telescope. Many of our objects have two apparitions during the two year (2014B-2016A) period. Often one apparition is in the southern hemisphere and the other is in the northern. This gives us flexibility in scheduling and enables the use of the 3 m NASA IRTF for the majority of the near-infrared spectroscopy component of this program.

The use of FIRE is critical to exploring the full size range. For example, the Massalia target list includes objects with objects from $\sim$1.6 km to $\sim$169 km. Using only the IRTF changes the lower size limit from $\sim$1.6 km to $\sim$4.3km. The sensitivity of FIRE is thus crucial to sampling an adequate number of objects in the smaller size ranges: in order to accurately study variations in the population all size ranges need to be sampled, not just the extremes.

3) C.A. Thomas is the PI of the program and any proposals submitted to the NASA IRTF and NOAO. Access to the Lowell Observatory telescopes will be provided by N. Moskovitz. This program was selected for funding by the 2013 NASA ROSES Planetary Astronomy program (PI: L.F. Lim/Science PI: C.A. Thomas).

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with `\related` command). **(up to one page)***

⋆ (1) We were awarded 1.5 nights at Magellan/Baade with FIRE for this program in 2014B. Some of this time was lost due to weather. The reduction pipeline for this program is under development.

(2) Trilling has been allocated six Magellan/FIRE nights over the past two years for a study of outer Solar System targets. The weather has been poor overall, but a paper presenting preliminary results is in progress.

(3) Trilling has been allocated 42 hours (2014A) and 60 hours (2014B) for a UKIRT program to measure the compositions of Near Earth Objects. First resutls from this highly successful program will be published by the end of 2014.

(4) Trilling leads the UAO part of a large consortium that is searching for additional flyby targets for the New Horizons spacecraft mission after its Pluto flyby in 2015. To date, six UAO Magellan/Megacam nights have been allocated to that project, as part of a large multi-institution, multi-telescope campaign. No more UAO observations for this project are planned. Some results from this program have been published in Parker et al. 2013 (AJ, 145, 96).

(5) Trilling and his postdoc Mommert have been allocated eight Bok/PISCES nights over two semesters for spectrophotometric measurements of KBOs in support of a Spitzer project. Although the 2014A conditions were not good, the data obtained is marginally useful, and has helped us plan our proposed 2014B observations, which are upcoming.

(6) Trilling has been allocated 14 nights on the VATT over the past two years to carry out spectroscopy of Uranian satellites. All data is reduced and the paper draft, led by UT graduate student Richard Cartwright, is circulating.