APPENDIX A: MAJOR OUTSTANDING ASTEROID COMPOSITIONAL QUESTIONS

Question	Possible Solutions	What Next?	Related Chapters
A. Formation and Physical Evolution of Asteroids			
1. Where, when, and how did they form?	*Where*: Links between asteroids and meteorites help constrain the conditions and location of formation. Dynamical models link where the asteroids are located now to where they originally formed. *When:* Recent advances dating mateorites have constrained formation ages. For example, igneous meteorites have crystallization ages older than chondritic ones. So bodies that melted, melted early. Bodies that did not melt formed later. *How*: A second leading theory on formation, through streaming instability, has emerged since *Asteroids III*.	Isotopic evidence points to carbonaceous chondrites being different from all others. But they are not all more water-rich, and their water H isotopes are not comet/Enceladus-like. Ages of chondrules and secondary minerals can be used to estimate chondrite formation ages. The almost ubiquitous presence of chondrules suggests that they may have played a role in planetesimal formation.	Section 4, this chapter, Johansen
2. How have they evolved physically?	Asteroid compositional changes are caused by early heating, acqueous alteration, and the external environment (space weathering). Physical changes are caused by impacts, radiation pressure (YORP spinup), and close approaches to planets (large tidal force).	Continued work on collisional and thermal modeling, studies of families, spacecraft measurements including surface (crater) observations. *In situ* measurements and sample return of non-OC-like bodies. Density measurements to understand interiors.	Brunetto, Krot, Scheinberg, Scott, Wilson, Bottke, Asphaug, Jutzi
3. How have they evolved dynamically?	Planetary migration likely plays a leading role in early solar system history. Planetary scattering, collisions, orbital drift, and orbital changes due to resonances dominate later history.	Identify the current spread in semimajor axis of each compositional group and use it to constrain the different migration scenarios. Search for and characterize interlopers for composition. Orbital and mass constraints also continue to inform dynamical history.	Section 3, this chapter; Morbidelli, Vokrouhlický, Bottke
B. Asteroid and Meteorite Compositions			
1. How many original parent bodies are represented in the asteroid belt?	Based on the meteorite record and the assumption that each meteorite group comes from a single parent body, there are at least 100–150 distinct parent bodies.	Meteor observation networks will provide insight on source bodies for meteorites. Continued work linking large main-belt asteroids to meteorites.	*Burbine et al.* (2002)
2. Can a single meteorite group be represented by more than one parent body?	(a) The simplest assumption is that each meteorite group comes from one parent body. (b) More than one object could have formed at a similar time and a similar distance from the Sun, in which case they might look very similar. For instance, there could be more original (>50–100 km) S-type asteroids than the three needed to explain the three ordinary chondrite groups.	Further research on meteorite composition will yield better understanding of parent bodies. For example, high-precision isotopic measurements may reveal if the OCs separate and demand more than three bodies. Sample return will provide insight, as will a review of how many primary parent bodies (those > 50–100 km) there are in each spectral class.	*Burbine et al.* (2002)

APPENDIX A (continued)

Question	Possible Solutions	What Next?	Related Chapters
B. Asteroid and Meteorite Compositions (continued)			
3. How well do meteorites sample the asteroids?	Comparison of meteorites with micrometeorites and breccias suggests meteorites may be fairly representative samples of the major types of asteroids. We still find new types of meteorites (and presumably parent bodies), but differences tend to be subtle. However, the inherent "top-heavy" asteroid size distribution means that rare, large collisions stochastically dominate the ejected fragments by mass, resulting in an inherent possibility of large devations from direct representation of asteroid types by meteorite collections. If there is more diversity in the spectra of main-belt asteroids than meteorites, could much of this diversity be due to regolith processes (grain size and density sorting) and space weathering? Also, there are biases associated with delivery efficiency from different resonances and the robustness of the samples as they past through Earth's atmosphere.	Characterize asteroids at sizes relevant to meteorite falls (~5–50 m) to compare with the meteorite collection. IDPs, micrometeorites, and clasts in meteorite regoliths provide alternative samplings of the asteroid belt — how similar are they to the meteorites?	Borovićka, Jenniskens, Binzel
4. How robust are our asteroid-meteorite links?	A few connections are robust: OCs make up part of the S class. HEDs are linked with V-types and the largest group of isotopically linked HEDs are concluded to be from Vesta. Isotopically distinct HEDs, as well as the diversity of other achondrites, point to a wide diversity of differentiation processes that remain poorly understood. The CMs may be linked with Ch and Cgh asteroids. The weaker and fewer bands present in an asteroid spectrum, the less confident we are of its composition. The C and X complexes could be extremely compositionally diverse, but observations are also affected by varying grain size, phase angle, regolith gardening, space weathering, etc. Shock darkening, which also mutes absorption bands, can also disguise the compositional identity of asteroid surfaces.	Dynamical study of asteroid families has the potential for addressing this question. By determining the ages of families and comparing with meteorite shock ages, and by following the plausible dynamical routes from family to Earth, current best guesses of associations of some meteorite types with families might become more robust. The mid-IR may be the next frontier for groundbased observational studies. Meteorite studies of spectral effects not related to composition are needed. Asteroid sample return will provide valuable insight for featureless asteroids. Serendipitous observation and recovery of objects such as 2008 TC_3 will also provide "free sample return."	Vernazza, Brunetto, Yoshikawa, Reddy, *Burbine et al.* (2002)

APPENDIX A: (continued)

Question	Possible Solutions	What Next?	Related Chapters
B. Asteroid and Meteorite Compositions (continued)			
5. How well do NEOs represent the main belt and beyond?	We now understand that dynamical and weathering processes can be relatively fast, suggesting that NEO flux is just a current snapshot, influenced by stochastic events like more recent disruption events. Size might also matter, and the speed at which an asteroid's orbit drifts due to the Yarkovsky effect increases with proximity to the Sun and with decreasing diameter. Yarkovsky is more effective at the small sizes (10 m or smaller) that might dominate meteorite samples. Additionally, size-dependent delivery mechanisms (Yarkovsky) mean that different size ranges could be dominated by specific asteroid families. NEO lifetimes and the NEO delivery models have helped link NEOs to their main-belt source regions.	Survey main-belt asteroids at sizes similar to NEOs (~1 km). Study dynamical and compositional links between NEOs and main-belt families and specific regions. Dynamics need to be calibrated by observations. New understanding of differentiation processes is also relevant.	Binzel
6. What is the diversity of compositions within individual small asteroids? What processes mix wildly different meteorite types into a single tiny body (e.g., Almahatta Sitta, Kaidun)? When did the mixing occur?	Collisional or accretional processes (or both) could potentially bring such diverse materials together.	Implementation of ATLAST-like telescopic surveys of asteroids/meteoroids on their final approach to Earth and increased video surveillance and recovery of fall samples to understand the prevalence of and compositions of these mixes. Physical measurements of the smallest asteroids (5–100-m). Sample return of small asteroids will also provide constraints.	Section 5.3, this chapter; Borovićka, Bottke?
7. The ordinary chondrite paradox: Why does the most common asteroid type, S-type, not match the most common meteorite type, OC?	Space weathering is the primary reason for the spectral mismatch. Laboratory experiments plus ground- and spacebased asteroid measurements made great progress. Hayabusa's sample return of Itokawa provided conclusive evidence. Other factors affecting spectral slope include grain properties and observational phase angle.	This question is solved. The follow up questions are: What S-type asteroids are not OCs? What meteorites do they supply? How does the space environment affect other asteroid types?	Section 5.5, this chapter; Vernazza, Brunetto, Binzel, Yoshikawa
8. What are the interior compositions of asteroids?	Density measurements and asteroid families currently provide the most information about asteroid interiors. How compositionally homogenous or differentiated the medium to large asteroids are is largely unknown.	Density measurements particularly from multiple systems. The porosity of asteroid interiors must be better constrained as well.	Margot, Scheeres, Barucci

APPENDIX A: (continued)

Question	Possible Solutions	What Next?	Related Chapters
C. Asteroid Compositional Distributions			
1. What is the source of the compositional gradient in the main belt? Why are the Hildas and Trojans compositionally homogeneous compared to the main belt?	(a) It is a primordial remnant from the temperature and compositional gradient in the disk. (b) It is the result of a transplantation of one or more groups of asteroids that formed elsewhere. (3) Hildas and Trojans actually are more compositionally diverse than they appear, but they have significant quantities of low-albedo materials that render diagnostic spectral features nearly invisible.	Progress on early solar system environment models and asteroid formation models. The best although impractical way to solve this is a mineralogical and isotopic assay of dozens of asteroids and comets.	Sections 2.2, 2.3, 5.1, this chapter; Morbidelli, Johansen, Emery
2. How does the distribution of asteroids change as a function of size? What is the significance of that distribution?	Recent work has explored the change in relative abundance of asteroid types as a function of size. Many factors still need to be taken into account, such as (1) the size-frequency distribution of families, (2) the difference in collisional lifetimes per asteroid class, and (3) the fact that some compositions are masked at smaller sizes due to processes such as collisions and "shocking."	Additional study of the size distribution of families in the inner belt. Groundbased imaging and shape models plus mission visits to primitive bodies. Constrain how prevalent shocking is in the main belt. Larger samples of small asteroids in the main belt (1–20 km) will help determine the distribution at smaller sizes.	Section 5.2, this chapter
3. The missing mantle problem: Where is all the missing mantle material? Additional questions: Why are V- and A-types scattered throughout the entire main belt?	(a) Asteroids differentiate differently than expected — perhaps they don't form large olivine-rich mantles and pyroxene-rich crusts. (b) The parents of these cores formed in the terrestrial planet region. They were destroyed and only the strongest metallic fragments were subsequently delivered to their current locations in the main belt. (c) "Battered to bits" — this theory is currently less favored. Collisional modeling, crater counts, and observational evidence do not support an aggressive regime of collisional destruction and battering. (d) Previous theories postulated olivine was hidden by weathering processes. Recent progress on on space weathering disproves this hypothesis.	Further study of dynamical solutions and differentiation modeling. Continued study of meteorites to understand differentiation. Continued search for differentiation in families, including metal within large families.	Section 5.4, this chapter; Scheinberg, Wilson, Scott
4. Where is the water in the asteroid belt? How much is there? Where did these water-rich asteroids form?	Current evidence: main-belt comets, activated asteroids, water absorptions, Ceres outgassing, and possible exposures of ice on Ceres.	Discover additional active asteroids and explore asteroid-comet connections. Continue studies of extinct or dormant comets among NEOs. Visit and map surfaces such as by the Dawn, OSIRIS-REx, and Hayabusa-2 missions. Also, density measurements, radar sounding by spacecraft, etc., might reveal ice buried beneath thick surficial lag deposits.	Jewitt, Rivkin, Krot, Binzel

APPENDIX A: (continued)

Question	Possible Solutions	What Next?	Related Chapters
D. Asteroids in Their Greater Context			
1. Importance of the asteroid belt for Earth: Do we have remnants of Earth's building blocks? Do we have remnants of Earth's water source?	Arguments exist for and against enstatites or angrites being primary components of Earth. Water from Earth's oceans is argued to have been delivered from asteroids. Late veneer. Isotopic compositions show that the known chondrites were not the major building blocks of Earth, but the CI + CM-chondrite-like material may have been the sources of Earth's volatile materials as suggested by the SMOW D/H ratio.	Continued studies of D/H ratios of meteorites, comets, and asteroids. Continued theoretical studies of planet formation and dynamical studies of planet and planetesimal migrations.	Section 6.1, this chapter
2. Importance of the asteroid belt for the rest of our solar system?	Surface ages determined by impacts and cratering rates. Main belt and Kuiper belt orbital architecture and captured Trojans and satellites constrain giant planet migration. Study of solar corona is enabled by asteroids and comets evaporating during close approach to the Sun.	Continue with current progress on crater studies, dynamical studies including migration.	Beyond the scope of this book
3. What role do asteroids play in other planetary systems?	Collisions in massive asteroid belts create debris disks around old stars.	Identify and characterize extrasolar asteroid belts (evolved debris disks). Survey different planetary system architectures including asteroid belt distances and masses.	Section 6.2, this chapter; mostly beyond the scope of this book
	Asteroids are tracers of dynamics and physical properties in dusty white dwarf systems.	Identify and characterize dusty white dwarf systems, and link those systems to the expected properties of precursor planetary systems.	
4. What role do asteroids play in creating the conditions for habitability on Earth-sized planets?	Meteorites are known to contain water and organics (including amino acids), which could be precursors for life. They represent the initial conditions and compositions for forming terrestrial planets. They could be responsible for water delivery and creating oceans. They could also be responsible for destroying life through impacts.	Understand the link or the gradient between comets and wet asteroids. Measure the D/H ratio of a wider array of water-rich small bodies. Dynamical studies of delivery. Understand consequences of delivery of too much water. Studies of impact and water retention on Earth. Studies of ocean-forming mechanisms unrelated to small-body delivery.	Beyond the scope of this book
5. What is the importance of asteroids as as hazards and resources for Earth?	Asteroids as a hazard have motivated increased attention to discovery surveys. Asteroids contain rare-Earth elements, including metals of value. Asteroids contain water or water components useful for space travel.	Discover 90% of PHAs down to 140 m. Understand the size of the small NEA population (<140 m). Evaluate and prepare for deflection strategies or evacuation plans. Continue to explore asteroids as resources.	Harris, Jedicke, Farnocchia