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A Guide to Asteroid-Meteorite Spectral Links

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Abstract： There are 24 asteroid spectral types in the Bus-DeMeo spectral classification system and about 27 meteorite mineralogical types. The spectral links between asteroids and meteorites vary a lot in quality and reliability because of challenges with the lack of diagnostic features in some mineralogies and the effects of space weathering. I will review what can be learned remotely from visible and near-infrared spectroscopy about asteroid mineralogy and how to understand asteroid spectral identifications from a geologist's point of view.

Keywords： asteroids；spectroscopy；mineralogy；space weathering；classification

Highlights：

- Asteroid spectral taxonomy does not imply a unique mineralogy for each class or subclass.
- Complicating any interpretation is space weathering，which is ubiquitous for asteroids， poorly understood for some asteroid mineralogies， and spectrally important.
- Spectral features only provide diagnostic identification of mineralogy for some asteroid types such as the S-complex and the A， K， L， Q， O， R， and V-types. Much of the taxonomic variation in these types of asteroids is probably caused by space weathering.
- The C and X-complexes and the D and T-types lack the diagnostic spectral information to unambiguously characterize their mineralogy. The low-albedo asteroids in these classes tend to be volatile-rich， moderate and high albedo asteroids tend to be anhydrous.
- Low albedo， weak， hydrated meteorites are probably very underrepresented in the meteorite collections relative to their actual abundance in the asteroid population.

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1 Introduction to Asteroid Spectroscopy and Taxonomy

How are meteorites and asteroids related to each other? Most meteorites come from asteroids (several groups of meteorites do come from Mars and the Moon). But which meteorites come from which asteroids? For the popular Bus-DeMeo asteroid spectral classification system based on visible and near-infrared spectroscopy[1-2] there are 24 spectral classes shown in Figure 1. For the meteorites that come from asteroids there are 27 meteorite groups. How do these two classifications relate to each other?

What we know about the mineralogy of asteroids comes largely from two sources: analysis of the meteorites that accumulate on Earth and the remote sensing of asteroids. The meteorite data has the advantage of state-of-the-art analysis techniques and is extremely detailed and precise[3]. The remote sensing data uses a wide range of wavelengths from visible, near-infrared, and thermal. This, coupled with albedo can be diagnostic of mineralogy in many cases[4]. However, severalasteroid typesdo not have spectral features that can provide diagnostic identification. In this paper we will review the data and techniques for characterizing

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meteorites and asteroids, highlight the links between these types, and review the problems and uncertainties in determining asteroid mineralogy from visible and near-infrared spectroscopy.

The spectral classification of asteroids has evolved over several decades. With limited spectral information classification started with three types: S (stony), C (carbonaceous), and M (metallic) [5-6]. With more and better spectral data the number of types has grown from 3 to the Bus-DeMeo 24 but it is not clear how many of these classes correspond to unique mineralogies. The Bus-DeMeo taxonomy specifically avoided the question of mineralogy by confining the taxonomy to spectral “features” analyzed in principle components space[1-2]. The first two principal components of asteroid spectra are typically the spectral slope and the strength of major mafic absorption bands [1-2,18]. In principle components space there are few natural divisions between the major asteroid spectral classes and typically all the classes blend into each other. Complexes and subtypes tend to occupy overlapping zones in principle components space. This feature-based approach only considered the variation seen in absorption bands and spectral slopes. Some of the variation is probably not the result of mineralogy, but of differences in surface texture, degree of space weathering, other unknown effects of the space environment, and variation or error in the observational techniques used[2,7]. While all of these factors add uncertainty to mineralogical identification, in many cases they do not preclude reasonable interpretation of the minerals and identification of probable meteorite analogues. In fact, a number of asteroid spectral types likely have identical mineralogies and just reflect modest variation due to the factors mentioned above.

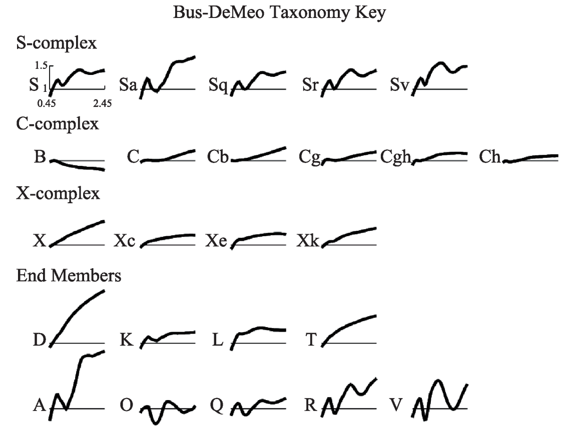

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Fig. 1 The Bus-DeMeo asteroid spectral taxonomy [1]

However, there are a number of asteroid spectral types and meteorite mineralogies that have no diagnostic spectral features and any mineral identification is at best ambiguous. An example of this is shown Figure 2. The spectra of a meteorite dominated by the iron-poor mineral enstatite, an iron-nickel meteorite, troilite (FeS) from the same meteorite, and a primitive volatile-rich carbonaceous chondrite are almost identical. The only real spectral features are the increase in reflectance with longer wavelength, a so-called “red slope” and a difference in brightness. In this case, lacking additional information, no spectral identification can be made and asteroids that may have wildly different mineralogies may share the same spectral class.

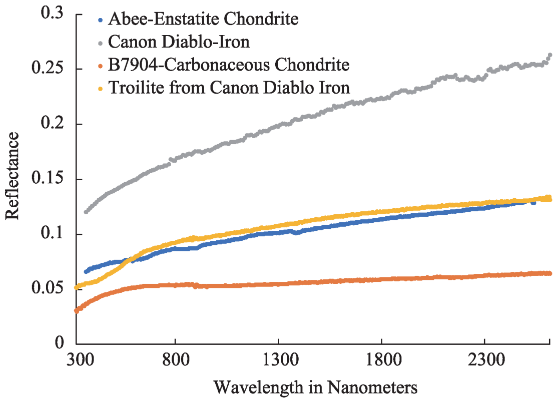

Fig. 2 The spectra of four featureless meteorites. These meteorites have wildly different mineralogies， but similar spectra because of the lack of strong absorptions in the visible and near-infrared

1.1 Meteorites and Bias

It is useful to remember that the meteorite collection is profoundly biased and cannot represent the diversity or relative abundance of asteroids. There are a number of factors that introduce bias and I will briefly review the major factors. ① The distribution of asteroid types in the solar system. The asteroid belt appears to be zoned with volatile-rich, hydrated, carbonaceous asteroids less abundant in the inner asteroid belt and less abundant near resonances that supply material to Earth-crossing orbits in the inner solar system[8-9]. ② The process of ejection of meteoroids. Ejecting boulders from asteroids is probably a mix of collisional processes and YORP effect spin-up. Survival from the shock and acceleration would bias the data toward strong materials[10]. ③ The collisional evolution of meteoroids. There is the potential for meteoroids to collide during their evolution toward Earth-crossing orbits. Again, collisions and shock will select against weaker materials since these materials are more likely to fragment completely. ④ The process of a meteoroid’s atmospheric entry at Earth. The process of deceleration in the atmosphere imposes substantial stresses on themeteoroid and strongly select against weak materials. Any fractures or imperfections in the structure with strengths below this limit will fragment, as reflected in the observations of bolides. ⑤ The final bias is the collection of the meteorite. The collection of meteorites is a very human process and is affected by a range of factors that include the local laws, the geology and fauna of the fall location (meteorites are difficult to find in forests, jungles or rocky terrain), the climate (wet climates rapidly degrade meteorites), population density (more people the more likely to find a meteorite), the local weather, and a range of other factors. Meteorite fall and recovery has only been a scientific enterprise for about 150 years, so the recovered numbers are still quite modest. This makes the analysis of many meteorite types and subtypes more difficult because of the statistics of small number.

1.2 The Basic Principles of Meteorite and Asteroid Spectroscopy

In all spectroscopy photons interact with the surface mineralogy of asteroids. Reflected and emitted photons carry wavelength dependent information about asteroid mineralogy. The fundamental quantum-mechanical interactions between photons and the mineral crystal structure result in wavelength-dependent absorptions or emissions that are diagnostic of the mineralogy. For asteroids in the visible and near infrared, some of the major optically active minerals are shown in Figure 3 and examples of meteorite spectra are shown in Figure 4. These include olivine which has a broad absorption centered at 1 micron, pyroxene with absorptions at 1 and 2 microns, and feldspar with a weak absorption at 1.3 microns. These absorptions are related the interaction of iron in the crystal structure of the minerals. Other absorptions are related to vibrational modes excited by photons in hydroxyls (OH) and water (H_2O) that is either bound in the crystal structure of

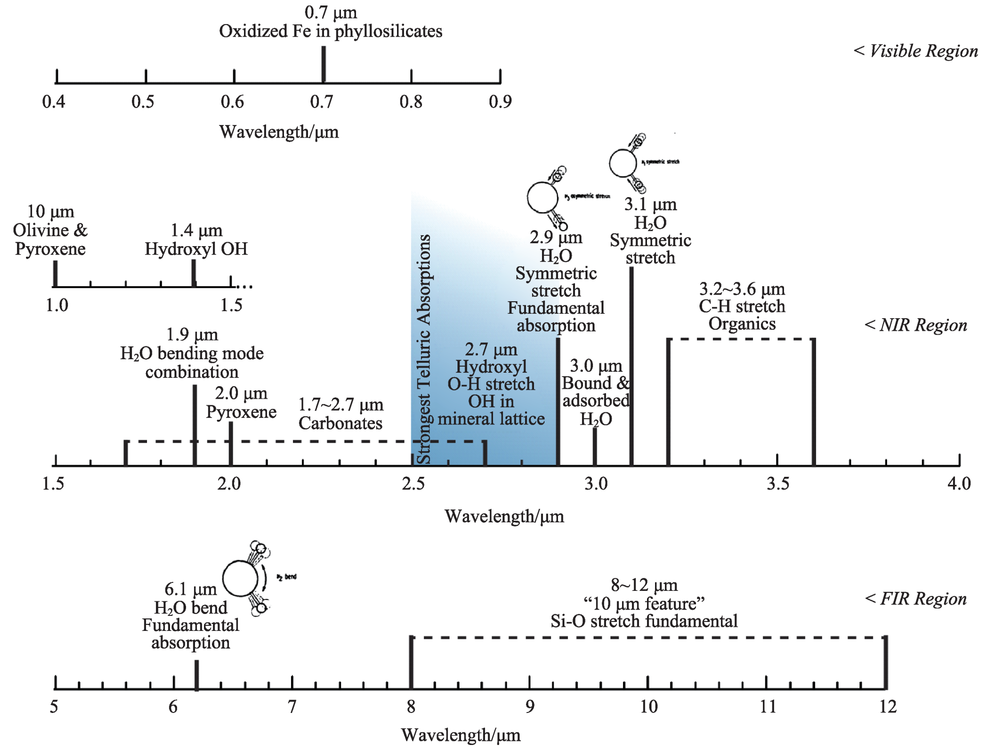

Fig. 3 Spectral absorption features of major asteroidal minerals

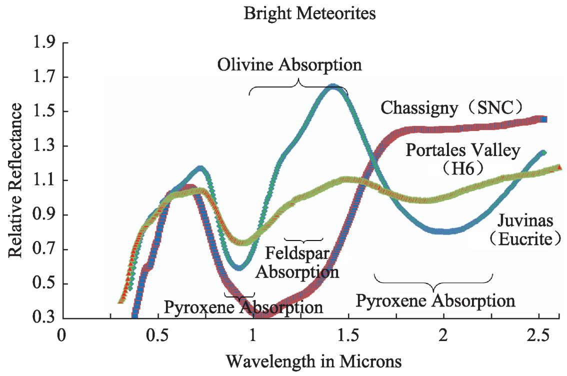

Fig. 4 Spectra of bright meteorites in the visible and near-infrared. Mineral absorption bands are labeled in the figure. For example， the blue spectrum shows strong pyroxene absorptions near 1 and 2 microns wavelength along with a weaker feldspar absorption at roughly 1. 3 microns

phyllosilicates or absorbed onto the mineral grains. Another vibrational absorption comes from the C-H stretch modes in organics.

Since the interactions depend photons interacting with the minerals, a key factor is the depth of photon penetration. Many minerals are relatively transparent so photons can often travel several millimeters through minerals before being scattered back out. But fundamentally photon penetration depends on opacity. Opaque minerals have elemental species that are highly absorbing of photons in the visible and near-infrared. Think ofcopy machine toner. It is composed of carbon materials that are so highly absorbing that it reflects less than 4% of the incident light. As a result, any photon has a very high probably of being absorbed and photon penetration into these materials can be as little as a few microns. As a result, meteorites that are rich in opaque materials may have compositions that include minerals with strong diagnostic absorptions, but those absorptions are masked and suppressed by the opaque materials. The result is that meteorites (and asteroids) can show similar spectra for very different reasons. As shown in Figure 2, the spectrum of enstatite looks similar to carbonaceous chondrite and iron meteorites.

The enstatite is transparent and has good photon penetration, but does not have optically active materials. The carbonaceous chondrite's mineralogy is dominated by optically active minerals, but has so many opaques in the form of organics or magnetite that it is darker than copy machine toner and thus has very little photon penetration.

1.3 Complications: Space Weathering

In addition to the problems with opaques and optically inactive minerals, the surfaces of all asteroids have been to a greater or lesser extent space weathered. Space weathering includes all the processes involved with the interaction of the space environment and the surface of the asteroid. This includes radiation damage, spallation from energetic particles, cosmic ray damage, the effects of hard vacuum, extreme cold or extreme heat, chemical reactions, solar wind implantation and damage, micrometeorite bombardment, shock and heating from impacts, comminution, vaporization, agglutination, sputtering, charging. Remember that all asteroids are covered with regolith. The regolith can be dusty or rocky depending on the size of the asteroid, but it is this surface that we are sensing with our remote instruments. We are NOT sampling asteroid bedrock.

What we know is that space weathering can strongly alter mineral spectra. The overall effect is shown in Figure 5. In this case the spectral data of meteorites and asteroids was resampled into the same spectral resolution and displayed in principle components space. The spectra of the two groups, which should have the same mineralogy, do not overlap. The direction and magnitude of the offset is due to know weathering effects. In silicates the known effects are to darken the reflectance and lower the albedo, attenuate otherwise strong absorption bands, and in some cases overprint the spectra with a red slope. The overall effect is to mask diagnostic spectral features and inject uncertainty into spectral identifications. Part of the

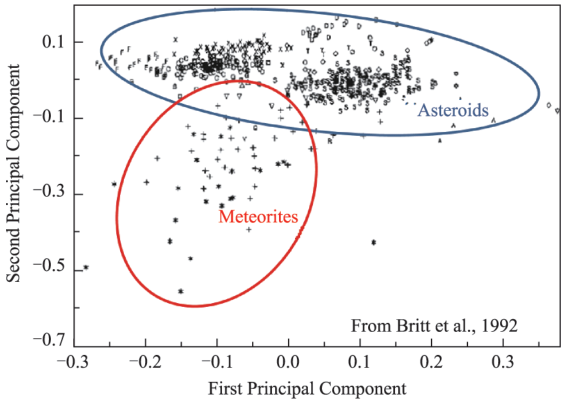

Fig. 5 The spectra of asteroids and meteorites in principle components space. The major spectral features of the two groups do not significantly overlap because of the effects of space weathering [18]

uncertainty is that the understanding of how minerals weather and the exact effects on their spectra are still in its early stages. While we beginning to understanding how iron-rich silicates weather, our knowledge of weathering in other materials, particularly carbonaceous chondrites is still rudimentary. Remember also that weathering is a dynamic process. A major impact can bring fresh material to the surface and reset weathering for an entire asteroid.

2 Spectral Interpretations

I am going to do what the Bus-DeMeo taxonomy specifically declines to do; make mineralogical interpretations of the spectral types and link those types to meteorites. In doing this I note that some types such as the S-complex and the A, K, L, Q, O, R, and V-types have strong absorptions that are diagnostic of mineralogy and can be linked to meteorites. However, this is not the case for all asteroids. The C and X-complexes and the D and T-types lack spectral absorptions. From the spectral point of view the only information is the degree of spectral slope which can be either flat, sloped in the blue direction, or sloped in the red direction. The problem is that, by itself, slope is not diagnostic of mineralogy, it merely denotes the lack of absorption features in the visible and near-IR. For example, the iron-poor pyroxene enstatite, iron-nickel, and very dark carbonaceous chondrites can all have the same spectral slope and featureless spectra. In this case the materials can be distinguished on the basis of albedo with enstatite being high albedo, iron-nickel having moderate albedo, and carbonaceous chondrite having very low albedo. But absent the albedo information these materials are spectrally degenerate and cannot be reliably identified.

2.1 S-Type Complex

The S-type asteroids and the related O and Q classes have the advantage for remote sensing that they are bright, stony, and with strong 1 and 2 micron absorptions. These types are highlighted in Figure 6. The spectral interpretation is that these objectsare largely composed of varying amounts of olivine and pyroxene and Fe-Ni metal. The spectra of these classes are shown in Figure 6. The major source of variation between these groups are the strength of the 1 and 2 micron bands, the degree of spectral redness, and the ratio of olivine to pyroxene. Most of these types are probably related to the ordinary chondrites which is the most abundant meteorite class seen in recovered meteorite falls. These meteorites are characterized by approximately equal amounts of olivine and pyroxene with 10～15 weight % iron-nickel metal.

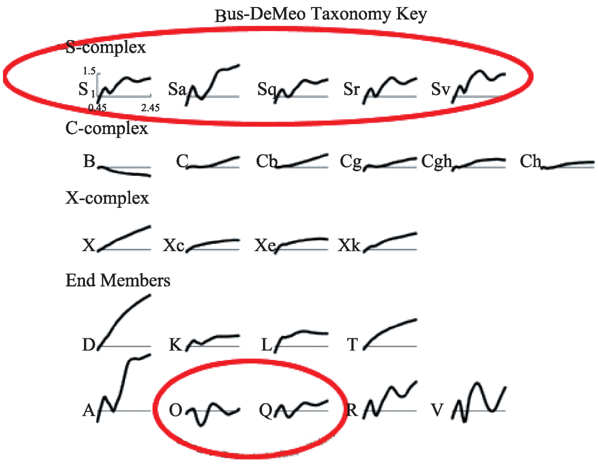

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Fig. 6 The S complex and related asteroids [1]

There are several smaller meteorite classes that have mineralogies similar to the ordinary chondrites and may have parent bodies that are included in the S-complex asteroids. The Mesosiderites are impact mixtures of olivine, pyroxene and larger amounts of metal. Since iron-nickel metal does not have spectral absorptions in the visible and near-infrared the contribution of metal to the spectrum is either neutral or reddening any silicate component would tend to dominate the spectrum. The pallasites are mixtures of large crystals of olivine with metal thought to sample the core-mantle boundary of a disrupted asteroid. This meteorite type would have the spectrum of an olivine-rich member of the S-complex. The IAB irons which are rich in silicate inclusions and theWinonaites are strongly related in mineralogy of the silicate component and in their oxygen isotopic ratios. They are thought to share the same parent body. However, since the IAB Irons would represent the core of the parent asteroid, this parent body would exist only in fragments and it is unlikely they have a large existing asteroidal parent body. The Lodranites have roughly equal amounts of metal, olivine and pyroxene. These meteorites are more metal rich than the ordinary chondrites, but spectrally similar so they may also have parent bodies in the S-type asteroids.

Olivine tends to spectrally redden with space weathering[11]and the S-complex in the main asteroid belt is reddened, probably by weathering. There is an observed relationship between the size of S-type asteroids and the degree of spectral reddening with larger asteroids being redder[12]. The interpretation is that size is a rough measure of surface age and thus degree of weathering. The spectra of the S-complex itself is reddened, probably from space weathering, the O and Q asteroids which are primarily found in the near-Earth population, which tend to have short lifetimes, are not weathered as much.

To interpret the mineralogy and meteorite links for the S-complex:

S and Sq, types: These are almost certainly weathered ordinary chondrites. Weathering shallows the absorption bands and reddens the spectra. As noted above, observers have noted a correlation between the spectral slope of main asteroid belt S type asteroids and asteroid size, with size being a rough approximation of surface age. As the surface age increases, the surface then weathers more and becomes more red[12].

Sr-type: This type is reddened with strong 1 and 2 micron pyroxene bands. However, the width of the 1-micron band indicates a component of olivine. Like the R-type asteroids, which these are spectrally related to, the mineralogy may be sub-equal amounts of pyroxene and olivine which describes ordinary chondrites. These asteroids may be just a variation of weathered ordinary chondrite, perhaps representing a higher metamorphic grade like the primitive achondrites, but with differential weathering that somewhat suppresses the olivine absorptions. Another possible meteorite analogue are Acapulcoites which have a mineralogy between H Ordinary Chondrites and Enstatite Chondrites.

Sa type: These asteroids are mostly olivine, probably more related to the A type asteroids than the other members of the S-type. They show little evidence of pyroxene and are most likely related to olivine-rich meteorites like Lodranites, Brachinites and Pallasites.

Sv-type: These asteroids are spectrally similar to the V-type, but with a redder spectral slope and shallower absorption bands indicating weathered V type material. As with the V-type asteroids, the meteorite analogues are the Howardite, Eucrite, and Diogenite (HED) meteorites which are thought to originate in the pyroxene-rich crustal material of a differentiated asteroid.

O and Q-types: These asteroids are primarily found in the inner solar system among the near-Earth asteroids. Since they are small and have relatively short lifetimes their surfaces have not had time to accumulate alteration by space weathering. The best analogue would be unweathered ordinary chondrites.

2.2 The A, R, and V types

These types asteroids again have the advantage for remote sensing that they are bright, stony, and with strong 1 and 2 micron absorptions shown in Figure 7. These are small groups. There is only one R-type asteroid (349 Dembowska), very few A-type asteroids, and the V-types are either 4 Vesta or probably fragments of Vesta. In a sense, the A and R types are a relic of a period in asteroid classification when the surveys and information on the asteroid belt was limited. Large, bright asteroids like 349 Dembowska (R) and 246 Asporina (A) were observed and classified early in the process of remote exploration of asteroids. Additional classes were added or subdivided, but few classes were deleted. It may be that the R and Sr, and the A and Sa classes need to be merged since the differences in mineralogy may be small to non-existent.

A-type: These asteroids are essentially all olivine and are related to the Sa type. They show little evidence of pyroxene and are most likely related to olivine-rich meteorites like theLodranites, Brachinites and Pallasites.

R-type:This type’s only member is the large main-belt asteroid 349 Dembowska. This asteroid is similar to the Sr types and is composed of strongly reddened(R for red) mixture of pyroxene and olivine. What is most likely is that Dembowska is composed of ordinary chondrite material, but with anolder surface age because of its large size. The extra reddening is probably related to surface age and weathering however weathering usually weakens the absorption bands and in Dembowska's case they are very strong.

V-type: Is Vesta (easy to remember) and (mostly) fragments of Vesta. However, there are V-types in orbits that make them unlikely to have originated from Vesta, so there were probably other fully differentiated asteroids like Vesta in the early asteroid belt that have subsequently been disrupted and fragmented. The mineralogy is pyroxene rich basalts and cumulative rocks with the HED meteorites as the meteorite analogues. We do see darkening and band suppression in the V's which is consistent with space weathering and the admixture of carbonaceous material coming from impactors.

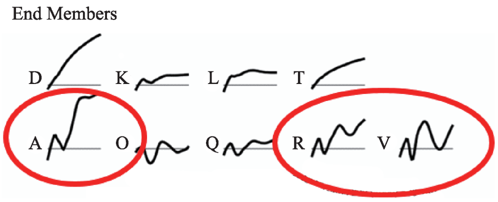

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Fig. 7　The A， R， and V types[1]

2.3　K and L Type Asteroids

The K and L-type asteroids show flat to moderately red-sloped spectra with subdued 1 and 2 micron absorptions diagnostic of olivine and pyroxene (Figure 8). This is a similar mineralogy to the S-complex, but less red sloped and with less spectral contrast in the absorption bands. These spectra are similar to the CO and CV carbonaceous chondrites. In a sense, these meteorites are miss-named since they have very little carbon, are anhydrous, and have mineralogies closer to the ordinary chondrites than other carbonaceous chondrites. Another spectral possibility are the shock blackened ordinary chondrites which aremineralogically identical to other ordinary chondrites but have been blackened by shock processes (Britt and Pieters, 1992). The overall effect of shock is to reduce the reflectance and shallow the absorption bands relative to normal ordinary chondrites.

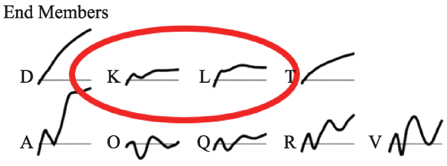

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Fig. 8　The K and L types[1]

K-types: The mineralogy is moderate albedo mixtures of olivine and pyroxene. The likely meteorite analogues are the CO and CV carbonaceous chondrites. Another possibility are the shock darkened ordinary chondrites.

L-types: Again the mineralogy is moderate albedo mixtures of olivine and pyroxene but with more subdued absorption bands. It is possible that additional space weathering or shock could produce more subdued absorptions on a bedrock CO or CV carbonaceous parent material. The likely interpretation is that these asteroids are more weathered CO and CV's.

2.4　The C Type Complex

The C-complex consists of the B, C, Cb, Cg, Cgh, and Ch types. They hard to interpret because there is just not much remote sensing spectral information available from these types of asteroids. With the previous types we have strong, high-contrast spectral bands that are diagnostic of silicate mineralogies. Not all silicate mineralogies have strong absorptions in observable wavelengths and those that do can be masked by a number of factors. Remember that spectral information depends on having photons interact with the crystalline silicate, undergo multiple scattering events from crystal surfaces, lose some photons to wavelength-dependent absorptions diagnostic of the crystal structure, and be scattered back out of the crystal. Having spectral information from reflectance depends on having photon path lengths long enough to interact with the material and be reflected out. The problem with C-complex asteroids and their meteorite analogues is that they are very dark. Reflectances for both asteroids and meteorites are in the 3%～6% range which is likecopy machine toner. This is due to a high content of opaque materials including magnetite and organic carbon compounds. The result for remote sensing is that the photon path lengths for these materials are shortened by orders of magnitude. Essentially the only reflectance information that survives an encounter with these very dark materials are the "first surface" reflections that do not penetrate the surface, do not interact with the minerals, and thus do not contain much spectral information. What we typically see from these types of asteroids and meteorites are variations in spectral slopes and that is not very diagnostic of mineralogy. So the essential remote sensing data on the C-complex are two facts, they have flat reflectance spectra and very low reflectance.

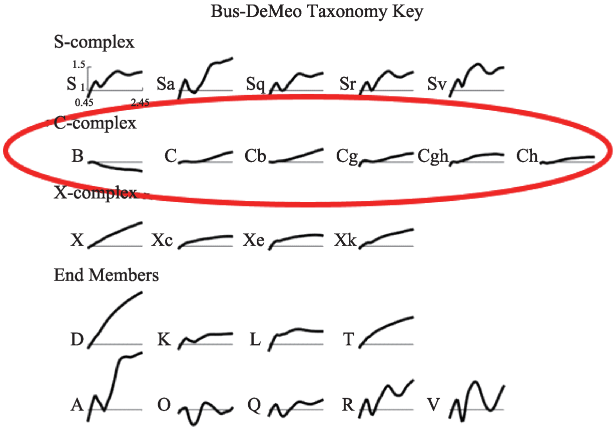

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Fig. 9 The C-complex [1]

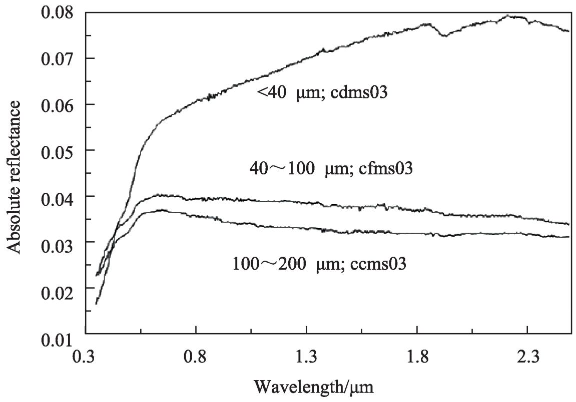

Fig. 10 Spectra of different particle sizes of the CI carbonaceous chondrite Orgueil[13]

The reasonable meteorite analogues for the C-complex are the volatile-rich carbonaceous chondrites, the CI, CM, C2, and CR carbonaceous chondrites. These meteorites have mineralogies that are rich in the hydrated phyllosilicate serpentine and the iron oxide magnetite. Minor minerals include the mafic silicate olivine, a range of hydrated clays, and varying amounts of organics. Their spectra are generally flat to strongly red sloped and their reflectances are very low. Essentially all the spectral information available from these meteorites is in the slope of the spectrum, but the slope is not diagnostic of mineralogy. Take for example the CI carbonaceous chondrite Orgueil shown in Figure 10[13]. The three spectra are from the same meteorite, but the variation in spectral slope ranges from strongly red sloped, to flat, to blue sloped. The only difference is in the particle size of the material with the fine particle sizes being the reddest and the course particle sizes being the bluest. However, this effect is not consistent between different samples of the same meteorite. Other published spectra of Orgueil show a strong blue slope with the finest particle size fraction[13]. We see a similar story with the other volatile rich carbonaceous chondrites. CM meteorites are very dark and can be strongly red sloped or spectrally flat depending on the meteorite, the particle size, or the sample processing[14]. CR and C2 carbonaceous chondrites essentially tell the same story of low albedo and flat to strongly red sloped featureless spectra depending on the meteorite and particle size[15]. Another factor to consider are the effects of space weathering and thermal processing. These meteorites are composed of low-temperature minerals such as serpentines that will alter and decompose at modest temperatures prevalent in the inner solar system[16]. This alteration is poorly understood in space conditions and would probably add to the spectral variability of the C-complex.

B, C, Cb, Cg, Cgh, and Ch types: As discussed above, the major distinguishing feature of this complex is the lack of spectral information. About the only spectral information is the slope, which can vary for a number of reasons. The most likely meteorite analogues are the CI, CM, CR, and C2 carbonaceous chondrites but the slope variation even within a single meteorite can more than cover the range of variation in this complex[13-15]. The particle size and texture of the regolith may play a major role in the shape of the spectra. Weathering and thermal effects, particularly for NEA’s are probably significant.

2.5 The X Type Complex

X complex includes the X, Xc, Xe, Xk, along with the D and T-type and the spectra is shown in Figure 11. Again these spectra do not have much information other than a moderate to strong spectral slope. The problem with this complex is the lack of spectral information was shown in Figure 2. Iron-poor silicates have essentially the same spectra in the visible and near-infrared as iron, troilite (FeS), and dark organic matter. The major distinguishing feature of these materials and the X-complex asteroids is albedo or brightness. However, albedo is not a factor in the Bus-DeMeo taxonomy so X-type asteroids that have ~40% albedo are classified together with asteroids that have 4% albedo. Since this is a feature based taxonomy, without spectral features there can be essentially no separation between these objects.

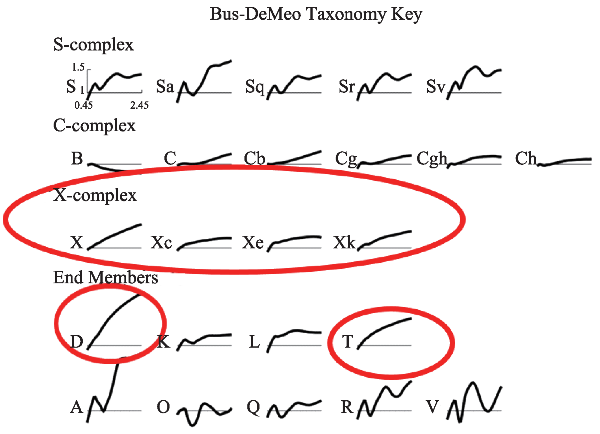

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Fig. 11 The X-complex

Xe and Xc types: Xe and Xc asteroids with high albedos are very likely composed of iron-poor enstatite. The enstatite chondrites and achondrites show spectral characteristics that cover the spectral range of these groups. These types of asteroids are often found in the Hungiara asteroid family near the inner edge of the main asteroid belt.

Xk type: These asteroids are often show medium albedos of roughly 20% and are probably composed largely of iron nickel metal whose meteorite analogues are the iron meteorites. A number of X type asteroids have been shown to have high-radar albedos[17] indicating a surface material rich in conductive materials like metal. The meteorite collection includes irons from probably 40 different parent bodies. It is likely that most of these parent bodies are the surviving iron cores differentiated asteroids that were stripped of their silicate mantles by collisional processes early in solar system history.

X and Xc types: The low albedo members of the X complex have mineralogies that are probably similar to the parent bodies of the volatile-rich carbonaceous chondrites. Again, the real distinguishing feature is not the spectral shape, but the albedo of the body. Albedos of ~4% are almost certainly driven by a strong component of very dark organic materials which is what are found in C2 and CI carbonaceous chondrites.

T-type: The spectra of the common meteoritic accessory mineral troilite (FeS) makes a good analog for the spectra of T-asteroids. Troilite is found most abundantly in ordinary chondrites, iron meteorites, and carbonaceous chondrites. However, since troilite is an accessory mineral it is mostly less than 5 wt. % of any meteorite and we do not have any pure troilite meteorites in the collections. It is unlikely that we actually have asteroid surfaces dominated by troilite, but more likely that T-type asteroids are dominated by iron-nickel metal with a somewhat stronger red slope than is seen in the general X-complex population, possibly due to space weathering.

D-type: The dominant characteristic of D type spectral is the very strong red spectral slope with almost no other spectral information. D type asteroids also tend to have very low albedos. The likely mineralogy is again similar to the C-complex, volatile-rich carbonaceous chondrites with strong components of opaque minerals and low-temperature organics. The C2 carbonaceous chondrite Tagish Lake has been suggested as an analog. The very red CI’s are also reasonable analogs.

3 Classification in Action-The Toutatis Flyby

During December 2012 the Chang’e-2 executed a remarkable flyby of asteroid 4179 Toutatis[19]. The flyby was even more remarkable because the spacecraft was repurposed from a lunar orbiting mission to an asteroid flyby mission. The most remarkable accomplishment was execution and control of an extremely close flyby with a surface miss distance of approximately 770 meters[19-23]. This is orders of magnitude closer than other flyby spacecraft have attempted. The science produced was spectacular and included high-resolution imaging of boulders, regolith, cratering, fractures, and an overall rubble pile structure for the asteroid[19-23]. The remote spectral data indicated that Toutatiswas a very red S-complex asteroid, classified as an Sq in the Bus-DeMeo system[24]. This pointed to a weathered ordinary chondrite composition and the spectral analysis suggested L ordinary chondrites as the most likely meteorite analog. What is remarkable about the spectra was the degree of reddening, attenuation of absorption features, and the reduction of albedo. All this indicates a surface with long exposure to the space environment and strong space weathering. The Chang’e-2 imaging strongly confirmed that remote result, showing a surface blanketed in thick regolith, covered with boulders with a steep size distribution, a rubble pile structure, and a substantial surface age for a near Earth asteroid[19-23]. This result shows the power of linking remote observation with spacecraft flyby imaging to produce a deep understanding of an objects mineralogy, evolution, surface processes, and structure. Because of the potentially hazardous nature of Toutatis, these data are exactly the sort of insight necessary for future planetary defense.

4 Conclusions

Asteroid taxonomies in general, and the Bus-DeMeo taxonomy in particular, are based on spectral features in the visible and near-infrared wavelength regions. The designers of this taxonomy do not imply a unique mineralogy for each class and subclass. The features do not necessarily provide diagnostic information on the mineralogy of any asteroid. In asteroids where features like mafic silicate absorptions are strong and high contrast, mineralogical interpretations can be diagnostic of mineralogy. In asteroids where diagnostic visible and near-infrared absorptions are lacking, many of the interpretations are going to be non-unique without additional information such as albedo and thermal infrared spectra. Complicating any interpretation is space weathering, which is ubiquitous for asteroids, poorly understood for some asteroid mineralogies, and spectrally important.

Spectral features only provide diagnostic interpretations of the mineralogy of some asteroid types. Between our knowledge of meteorite spectra and mineralogy, and our understanding of space weathering it is possible to characterize the mineralogy of the S-complex and the A, K, L, Q, O, R, and V-types. Much of the taxonomic variation in these types of asteroids can probably be ascribed to space weathering. For example, ss we discussed above much of the S-complex, the Q, and O asteroids probably are the same material at different stages of space weathering.

The C and X-complexes and the D and T-types lack the diagnostic spectral information to unambiguously characterize their mineralogy. With additional information such as albedo, we can make useful interpretations of the C and X-complexes. For example in characterizing the potential of asteroids for volatile extraction, the most diagnostic feature is albedo. Low-albedo asteroids tend to be volatile-rich, moderate and high albedo asteroids tend to be anhydrous.

A final factor to remember is that we probably do not have meteorites from all the possible spectral types of asteroids. Low albedo, weak, hydrated meteorites are probably very underrepresented in the meteorite collections relative to their actual abundance in the asteroid population. There are probably still “undiscovered” meteorite groups in the solar system that have yet to be found and recovered for the meteorite collections.

In general taxonomy needs to be treated as a guide to understanding asteroid mineralogy. In many cases the guide is diagnostic and fairly precise. But in a number of cases, the diagnostic information is simply not there in the asteroid reflectance spectra.

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小行星与陨石的光谱联系

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摘　要：Bus-DeMeo光谱分类系统中有24种小行星光谱类型以及约27种陨石矿物学类型。小行星和陨石之间的光谱联系在质量和可靠性上差异很大原因主要是某些矿物学中缺乏诊断特征和空间风化作用。将回顾从可见光和近红外光谱中远程获取的小行星矿物学信息，讨论如何从地质学家的角度理解小行星的光谱辨识。

关键词：小行星；光谱学；矿物学；空间风化；分类

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