Reports

Compositional Structure of the Asteroid Belt

Abstract. *The distribution of compositional types among the asteroids is found to vary systematically with heliocentric distance. Seven distinct peaks in the relative proportion of the compositional types E, R, S, M, F, C, P, and D are found from 1.8 to 5.2 astronomical units. The inferred composition of the asteroids in each semimajor axis region is consistent with the theory that the asteroids accreted from the solar nebula at or near their present locations.*

Studies of the physical properties of the asteroid system are of fundamental importance for our understanding of the formation and early evolution of the solar system. The location of the asteroid belt between the orbits of the silicate-rich terrestrial planets (Mercury, Venus, Earth, and Mars) and the volatile-rich outer planets (Jupiter, Saturn, and so on) makes the asteroids potentially important probes of the thermodynamic conditions (*1*) between these two classes of planets.

Theoretical and physical studies have supported the idea that the asteroids, which are much smaller than the planets and most natural satellites, represent the remnants of a population of planetesimals that have undergone relatively little geochemical alteration since their formation. The combination of spectral reflectance observations and albedo determinations can be used to infer compositions based on the presence or absence of mineral absorption bands and the absolute reflectance. If most of the asteroids formed near their present locations, then the matching of asteroid compositions to specific minerals or meteorites will suffice to trace the thermodynamic trends. However, if most of the asteroids formed elsewhere and were transported over significant distances into the orbits they occupy today (*2*), then additional problems in celestial mechanics must be addressed.

The discovery that the distribution of compositional types in the region from 2.2 to 3.2 AU was not constant with heliocentric distance (*3, 4*) led to considerable speculation about the origin of the asteroids. Table 1 shows qualitative descriptions of the major types included in the Tucson revised index of asteroid data (*5*) plus the new types F, D, and P. A more quantitative description of these types can be found elsewhere (*4–7*). It should be noted that of the three largest asteroids Pallas and Vesta are not classifiable in this scheme and that Ceres (diameter ~ 1000 km) is an "unusual" type C. Anders (*8*) and Zellner (*4*) suggest that the variation in types S and C is a primordial feature, although others (*2*) point out that there are too many irregularities in the distribution of size versus type to consider the S-C variation necessarily primordial.

Previous studies of the distribution of compositional types have been limited by (i) the assignment of compositional type to an asteroid solely on the basis of limited spectral data (generally UBV photometry) and (ii) lack of observations of asteroids with orbits of semimajor axes less than 2.2 AU or greater than 3.0 AU. Type assignments based on spectrophotometry alone can be misleading, especially in the case of types E, M, and P. In the case of type P, the spectral characteristics from 0.3 to 1.1 μm are indistinguishable from those of type M, and many P types have been previously assigned an M classification based on spectrophotometry alone. However, the P asteroids have visual geometric albedos which are similar to those of type C ($p_V < 0.065$) rather than type M ($p_V = 0.07$ to 0.23)—hence the name pseudo-M or type P (*7*).

We used a variety of observations, mainly albedos (reflectivities) derived from 10- and 20-μm radiometry (*7, 9*) and eight-filter (0.3 to 1.1 μm) broadband spectrophotometry (*10*), to show that the asteroid belt is highly structured in composition. In particular, we report on the bias-corrected distribution from 1.8 to 5.2 AU of the previously defined (*3, 4*) compositional types C, S, E, R, and M, plus type D and the newly described types F and P. We note that the selection of objects for radiometric and spectrophotometric observation from among the most poorly observed asteroid classes—including small main belt asteroids, outer belt asteroids, and asteroids with ambiguous classifications—has had a significant effect on our understanding of the distribution of types.

We are interested in the true rather than the apparent distribution of taxonomic types. Therefore, several observational biases in the data must be taken into account. These include (i) effects due to the incompleteness of the observed asteroid population, (ii) the bias toward the observation of nearer, larger, higher albedo (hence brighter) asteroids, and (iii) effects due to the selection of certain asteroid families for intensive study at the expense of field objects in the same part of the belt. The first two biases were corrected by using techniques first applied by Zellner and Bowell (*4*) to asteroids in the semimajor axis zones defined by Kiang (*11*). Only asteroids with mean opposition magnitudes $B(a,0) \leq 16.5$ were retained in the sample. However, this approach introduces the complication that the cutoff at small diameters is a function of heliocentric distance. The third bias was eliminated by identifying and discarding asteroids that are members of asteroid families which were targets of special studies (*12*), that is, the Flora, Nysa, Koronis, Eos, and Themis families. Finally, all planet-crossing asteroids were discarded since their formation locations, though unknown, are known to be different from where they are found today. At least four of the discarded families appear to have resulted from the disruption of homogeneous parent bodies (*12*). To counter the oversampling of these objects, each family has been represented in the analysis by assuming it to be one object of the most common type found in that family. The bias factor in each of Kiang's zones is the ratio of the typed asteroids (shaded portion of histogram in Fig. 1) to the total number of asteroids, including completeness corrections to the numbered population, where significant, in the bias-corrected sample.

Bias effects, especially in the new regions sampled, have been minimized by the nearly complete sample obtained. For example, in the Hungaria region, defined by Williams' families (*13*) 190 and 191 plus the Hungaria group, 12 of the 20 known objects in the bias-corrected sample have been observed by at least one method. Among the outer belt asteroids, 38 of 51 numbered Cybele mem-

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bers, 26 of 28 Hilda members, and 18 of 19 Trojans have been sampled.

The bias-corrected distribution of asteroid compositional types is illustrated in the lower half of Fig. 1, which shows the fraction of asteroids in each zone that are of a particular type. Some asteroids are not classifiable in the taxonomic scheme or are too few in number to show in Fig. 1. That fraction is simply one minus the sum of the typed fractions in each zone. Smoothed curves have been drawn for clarity.

Immediately apparent is the nonrandom distribution in semimajor axis for all types. A particular type or set of types dominates each region. For example, in the innermost region of the belt, the Hungaria region, the population is dominated by types E and R. These are high-albedo objects ($p_v > 0.23$) with either neutral spectral reflectances (E) or unusually reddened reflectances (R). Both of these types are compositionally distinct from type S, which dominates the next region. In terms of the relative abundances of the types discussed here, the asteroid belt appears to be composed of at least six major compositionally distinct regions.

Table 1. Summary of asteroid compositional types. Types C, M, E, S, R, and U are from Zellner (*4*). Type D is from Tedesco and Gradie (*7*) and was originally called RD by Degewij and van Houten (*6*). Types P and F are from Tedesco and Gradie (*7*).

Type	Visual geometric albedo	Spectral reflectivity (0.3 to 1.1 μm)
C	Low (< 0.065)	Neutral, slight absorption blueward of 0.4 μm
S	Moderate (0.07–0.23)	Reddened, typically an absorption band ~ 0.9 to 1.0 μm
M	Moderate (0.07–0.23)	Featureless, sloping up into red
F	Low (< 0.065)	Flat
P	Low (< 0.065)	Similar to M, hence pseudo-M or P
D	Low (< 0.065)	Very red longward of 0.7 μm
R	Very high (> 0.23)	Very red, bands deeper than S
E	Very high (> 0.23)	Featureless, flat or sloping up into red
U		Unclassifiable in this system*

*Includes Vesta, Pallas, and other unique objects which may be sole representatives of an undefined type.

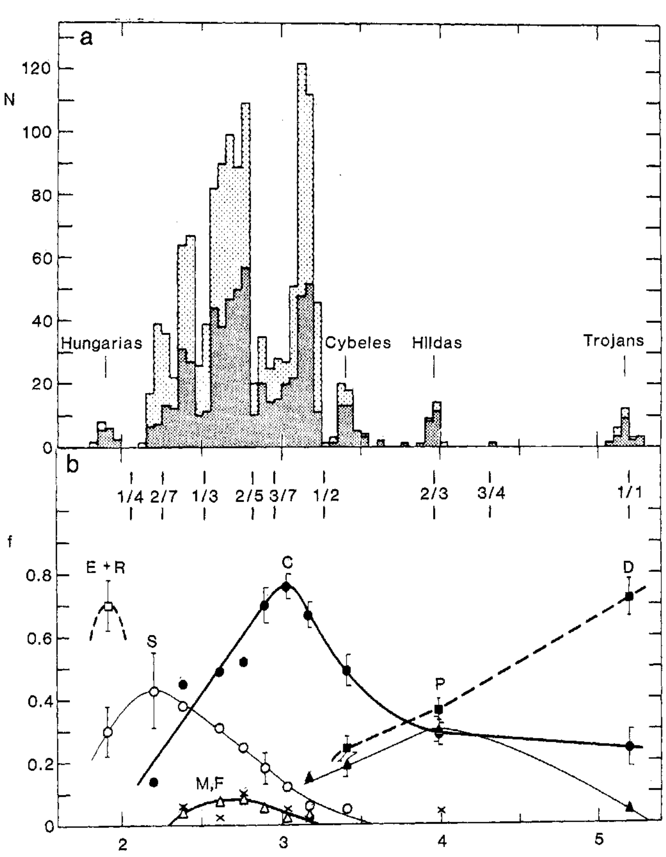

Fig. 1. (a) Number distribution in semimajor axis for the 1373 asteroids in our bias-corrected sample. The sample is corrected for observational selection effects (see text). The darkly shaded portion is the fraction of the sample (656 asteroids) for which taxonomic types exist. In the bias-correction technique it is assumed that the population characteristics of the unobserved part of each zone are identical to those of the observed portion. Major resonances with Jupiter are indicated. (b) Observed relative type distribution of the bias-corrected sample for the types listed in Table 1. Smooth curves are drawn through the data points of each type to more clearly delineate their distribution. (△) Fraction of type M, (X) fraction of type F. Error bars represent ±1 standard deviation uncertainties due to incomplete sampling. Error bars were not plotted for uncertainties less than 4 percent.

The observed relative abundances of the various types seen in the number distribution are not representative of the mass distribution since most of the mass is contained in a few large objects. It is likely that the observed abundances and their heliocentric distribution are artificially enhanced by collisional processes in spite of our effort to compensate for such effects by removing members of the major dynamical families from our sample. For example, the enhancement of type C near 3.0 AU may be the result of numerous fragments from large homogeneous C-like parent objects. Also, the largest type E (44 Nysa) does not appear in the E+R region. However, the systematic variation of all types around respective peaks argues strongly that the zones are not derived from numerous randomly distributed types. Furthermore, it is possible that some of the boundaries and peaks in the type distribution may have resulted from interactions with the major resonances with Jupiter.

In the outermost regions of the asteroid system the heliocentric distribution of asteroids is marked by wide gaps, which makes the type distribution somewhat more difficult to interpret. For example, there is only one asteroid between 4 and 5 AU—asteroid 279 Thule (a type D). In spite of these gaps, the general trends can be followed. For example, type D, which dominates the Trojan region (5.2 AU) but becomes rarer with decreasing heliocentric distance, disappears altogether at about 3 AU.

If the observed differences among the asteroid types are truly compositional in nature, then the type distribution can be interpreted as representing gross compositional changes across the belt. The implied differences in composition between the S asteroids (moderate-temperature siliceous condensates) and the C asteroids (low-temperature carbonaceous-rich siliceous condensate) (*14*) are consistent with those predicted from chemical condensation models of the solar system (*1*). It has been suggested that the composition of the outer belt and Trojan asteroids (type D), and possibly comet nuclei, is consistent with a low-temperature carbonaceous-rich silicate that condensed at temperatures and pressures lower than those for type C (*15*). The low albedo of type P is consistent with the presence of low-temperature opaques such as carbonaceous material, although other opaque substances cannot be excluded. Type E is thought to be consistent with higher temperature, spectrally neutral silicate condensates (*16*). However, it remains to be demonstrated conclusively that the mineralogy of the E, R, P, and D asteroids is consistent with this theory.

In conclusion, the asteroid belt is sorted into at least six compositionally distinct regions. It seems unlikely that the gross features of this distribution can be explained by the random transport of objects over large distances from other regions of the solar system; rather it appears that the asteroids formed at or near their present locations. When determined, the detailed chemical composition of the asteroids in each region can be used to provide constraints on the small-scale thermodynamic conditions of the solar nebula in the transition region between the terrestrial and Jovian planets.

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Low-Frequency Eddy Kinetic Energy Spectrum in the Deep Western North Pacific

Abstract. *The frequency spectrum for the low-frequency eddy kinetic energy is estimated from a long-term current meter record obtained in a deep layer in the western North Pacific. The eddy field is characterized by three time scales: an "annual scale" with zonal dominance of eddy motions, a "temporal mesoscale" with meridional dominance, and a "monthly scale" with horizontal isotropy. About two-thirds of the eddy kinetic energy is contained in the temporal mesoscale.*

Mid-ocean mesoscale eddies, either barotropic or baroclinic, seem to exist all over the world ocean, having typical time scales of weeks to months and typical horizontal scales of tens to hundreds of kilometers (*1*). Intensive observational studies of the eddies have been made, most of them in the western North Atlantic (*1*, *2*). Year-long current measurements have been made there and frequency spectra for the low-frequency fluctuations (frequencies less than one cycle per day) have been estimated (*3*, *4*). Several studies of the mesoscale eddies in the Pacific have been based on temperature and salinity measurements (*5*), but very few studies have been based on direct current measurements (*6*). We report here, for the first time, the spectral features of the low-frequency fluctuations, including the annual fluctuations, in the mid-ocean of the western North Pacific on the basis of a long-term current meter record.

A program of long-term deep current measurements by moored meters was started in October 1978 in the western North Pacific as a part of a preoperational survey of a proposed area for the disposal of low-level radioactive wastes. It is expected to continue over several years. The observation site is centered at 30°N, 147°E in the mid-ocean; it is about 500 km south of the Kuroshio Extension and about 400 km east of the Izu-Ogasawara Ridge. The water depth is about 6200 m, and the bottom topography is fairly flat with no pronounced slopes; the water depth varies from about 6000 to 6400 m within 100 km of the site center. The most prominent topographic feature is a small hill with a depth of 4890 m, located about 30 km north of the site center. The existence of low-frequency velocity fluctuations near the site was suggested by an earlier current measurement made over a period of about 3 months (*7*).

The mooring lines have been deployed and recovered four times at several stations. From these measurements, a continuous current meter record for 1020 days has been obtained in the deep layer at station RB, whose nominal position is 30°00′N, 147°08′E. It is the longest current meter record ever obtained in the mid-ocean of the world ocean (*8*). Aanderaa RCM-5 current meters were used.

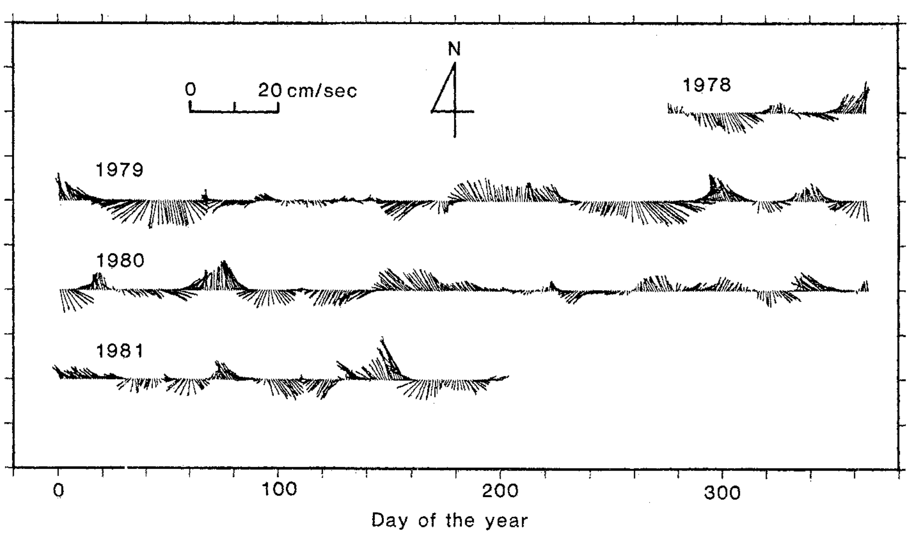

Fig. 1. Time series of daily mean current velocity observed at a nominal depth of 5000 m in the western North Pacific (30°00′N, 147°08′E) from 3 October 1978 to 18 July 1981. Each stick represents the daily current vector (upward north). The record from year day 327 in 1979 to year day 236 in 1980 was not obtained. Here it is justifiably made up for by a record at a nominal depth of 4000 m at the same station, because no significant differences in daily mean velocities between nominal depths of 4000 and 5000 m are recognized at that station or at the other stations at the site (*10*).

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