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S-asteroids 387 Aquitania and 980 Anacostia: Possible fragments of the breakup of a spinel-bearing parent body with CO3/CV3 affinities

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Abstract—Asteroids 387 Aquitania and 980 Anacostia are anomalous members of the S-class. Their reflectance spectra exhibit a strong broad absorption feature longwards of 1.5 μm and no significant feature near 1 μm. Their spectra indicate the presence of spinel, an aluminum-magnesium oxide mineral commonly present in inclusions in CV3 and CO3 meteorites. Spinel probably makes up only a small percentage of the surface assemblages of these asteroids, but its spectral effect may be enhanced by its presence in fine-grained white inclusions in immature asteroid regoliths. It is speculated that Aquitania and Anacostia represent material formed in the same nebular zone as the CV3 and CO3 chondrites but either: A) at an earlier time in the nebula when such inclusions might have been a relatively larger fraction of the nebular grain population, or B) in local regions where nebular processes (*e.g.*, settling to the midplane) had concentrated such inclusions. The close similarity of two orbital elements (a, i) suggests that Aquitania and Anacostia may be members of a partially dispersed asteroid family produced by the early disruption of a spinel-bearing parent body.

INTRODUCTION

The S-type is known to be a mineralogically diverse asteroid class (Bell *et al.*, 1989; Gaffey, 1990). The interpretation of most large S-asteroids as igneous bodies (*e.g.*, Gaffey, 1984; 1986; Bell *et al.*, 1989; Gaffey *et al.*, 1989; 1990) is still controversial but is increasingly supported by a wide range of evidence (*e.g.*, Gaffey, 1991). Analysis of S-asteroid reflectance spectra indicates that this population includes a wide variety of igneous metal-rich, mafic silicate assemblages ranging from pyroxene-dominated (pyroxenites, basalts, "mesosiderites") to olivine-dominated (dunites, peridotites, "pallasites") with olivine-rich mixtures (1.5 < ol/pyx < 6) predominating (Gaffey *et al.*, 1990). For a review of asteroid classifications, see Tholen and Barucci (1989).

However, it is also believed that at least a small subset of non-igneous (undifferentiated, chondritic) asteroids is present within the S-asteroid population defined by Tholen (1984). One subclass, the K-type which has been distinguished within the original S-population, has been interpreted as analogous to CV3/CO3 chondritic assemblages based upon IRAS albedos and near-IR spectra (Bell, 1988). This K-class is defined as objects that are found among the Eos family with albedos near 0.09, S-like spectral curvature at visual wavelengths, weak 1 μm absorption bands, and flat reflectance from 1.1–2.5 μm. The K-class has also been separated from the S-asteroids in the three parameter asteroid classification system of Tedesco *et al.* (1989). It is also commonly believed that at least a few of the large S-asteroids might be ordinary chondrite type assemblages.

TWO ANOMALOUS S-TYPE ASTEROIDS

Two S-type asteroids (387 Aquitania and 980 Anacostia (Fig. 1) were first identified as having anomalous 1.1–2.5 μm spectra during the mineralogical analysis (Gaffey *et al.*, 1990) of the S-asteroids in the 52-channel (*a.k.a.* 52-color) asteroid survey (Bell *et al.*, 1988). The typical S-type asteroid is characterized by two broad absorption features centered near 1 μm and 2 μm. The 1 μm feature is a combined absorption from olivine and pyroxene, while the 2 μm feature is due to pyroxene alone. The normalized intensity (band depth below a linear continuum fitted to points outside the band) of the 1 μm feature in S-type asteroids is less than 0.2. The normalized intensity of the 2 μm band is generally significantly less than that of the 1 μm band. The intensity of the 2 μm band only approaches that of the 1 μm band in pyroxene-dominated assemblages. The ratio of the areas of the 1 μm and 2 μm absorption features is a function of the relative abundance of olivine and pyroxene (Cloutis *et al.*, 1986).

Based upon these criteria, the S-asteroid 387 Aquitania and the SU-asteroid 980 Anacostia have spectral features which are not consistent with typical S-type asteroids. Both have band area ratios (4.2 and 6.8, respectively) inconsistent with known S-type olivine-pyroxene mixtures (0.0–2.8: Gaffey *et al.*, 1990). Both asteroids have a strong broad absorption feature near 2 μm with a very weak and poorly defined absorption feature near 1 μm. While the intensity of the 2 μm feature in the spectra of these two asteroids is not outside the range observed for S-asteroids, both lack the strong well-defined 1 μm pyroxene feature which inevitably accompanies it in typical S-asteroids.

These two asteroids were also subsequently identified as anomalous during principal component analysis (Burbine, 1991) of spectral data from the 52-channel asteroid survey. An independent neural network classification (Howell *et al.*, 1991) of the 52-channel asteroid survey data also noted that Anacostia had an unusual spectrum and linked it with both the T-class and their newly defined Sp (pyroxene-rich S-asteroids) class. However, Aquitania was not identified as unusual and was included in their Sp-class. Independently, these two asteroids were identified as anomalous by Britt and Lebofsky (1992).

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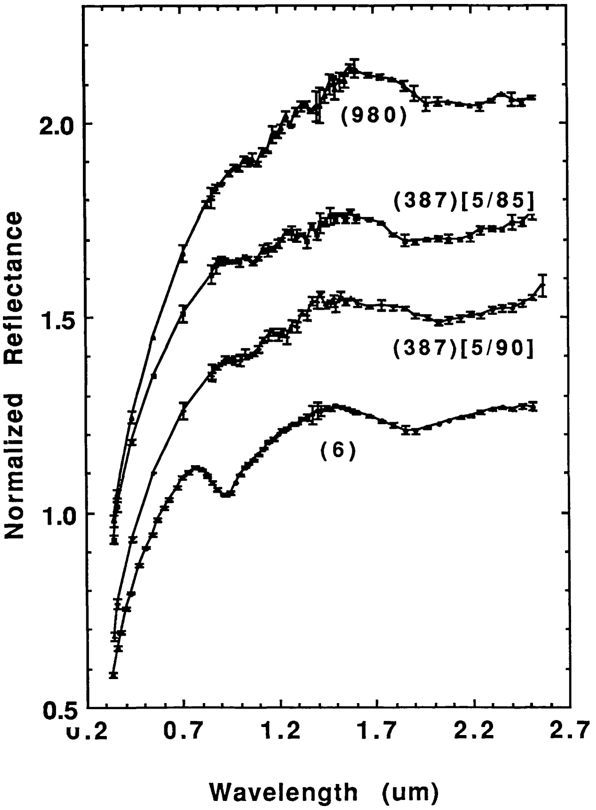

FIG. 1. The reflectance spectra of 387 Aquitania (1985 and 1990) and 980 Anacostia are compared to that of a typical S-type asteroid, 6 Hebe. All spectra have been normalized to unity at 0.55 μm for the ECAS data (387 and 980) or at 0.56 μm for the 25-filter data (6). A 2 μm feature is present in all spectra, but a 1 μm feature is present only in the Hebe spectrum. The difference between the 387 spectra near 1.9 μm is probably an artifact of incomplete correction of the terrestrial atmospheric water vapor absorption. For clarity, the spectra of 387 [5/90], 387 [5/85] and 980 are offset by +0.1, +0.35 and +0.45, respectively. Error bars are 1 sigma uncertainties of the mean.

TELESCOPIC SPECTRAL OBSERVATIONS OF AQUITANIA AND ANACOSTIA

The 52-channel asteroid survey spectra (0.8–2.6 μm) were measured through a circular variable filter (CVF) with a spectral resolution ($\Delta\lambda/\lambda$) of approximately 3% and with an indium-antimonide detector mounted in a liquid helium cooled dewar. Observations were obtained using this facility instrument mounted on the 3-m reflecting telescope of the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. Corrections for the instrumental response function, for the different atmospheric transmission as a function of wavelength and for different atmospheric path lengths as a function of zenith angle were made from comparison observations of calibrated standard stars using the techniques discussed by Chapman and Gaffey (1979). Atmospheric extinction coefficients were computed from the standard star observations for each night or for each discrete segment of a particular night.

TABLE 2. Physical and orbital properties.

	387 Aquitania		980 Anacostia	
Tholen class[a]	S		SU	
Proper orbital elements				
Semimajor axis (AU)	2.742[b]	2.739[c]	2.741[b]	2.741[c]
Sine of inclination	0.303	0.284	0.306	0.298
Eccentricity	0.200	0.229	0.117	0.131
IRAS albedo[d]	0.16 ± 0.01		0.17 ± 0.01	
IRAS diameter[d]	106 ± 5 km		89.0 ± 1.6 km	
Rotational period	24.1435 ± 0.0020 hours[e]		20.117 ± 0.004 hours[f]	

a) Tholen, 1989; b) Williams, 1989; c) Knezevic and Milani, 1989—version 5.7, updated 91/04/24; d) Tedesco, 1989; e) Harris *et al.*, 1992; f) Harris and Young, 1989.

Observations of asteroid 387 Aquitania were obtained by Bell on 1985 May 4 and those of 980 Anacostia were obtained on 1985 December 24. Other asteroids observed on those same nights [asteroid #'s 29, 352, 385 and 1036 on May 4; #'s 15, 258, 389, 511, and 1866 on December 24] exhibit different spectral features than Aquitania or Anacostia and either match previous spectral data for that individual object within their observational uncertainties or are plausible for the taxonomic type of the individual asteroid if no previous spectra existed. This indicates that the anomalous spectra of Aquitania and Anacostia were not spurious artifacts produced by instrumental or observational problems or by the standard stars used in the observing runs.

The anomalous spectrum of 387 Aquitania was confirmed by independent observations obtained on 1990 May 6 by Gaffey using the same instrument mounted on the NASA-IRTF telescope. The resulting spectrum provided a good match with the data previously obtained by Bell, although a data system problem increased the noise of the 0.8–1.5 μm portion of the spectrum. The specific conditions for each set of asteroid observations are given in Table 1. The physical properties of Aquitania and Anacostia are listed in Table 2.

The spectra of both observational sets for Aquitania and the set for Anacostia are shown on Fig. 1, along with the spectrum of a more typical S-asteroid (6 Hebe) for comparison. The ECAS spectra of 387 Aquitania and 980 Anacostia from Zellner *et al.* (1985) were scaled to the 52-channel data in the region of spectral overlap and were used to extend spectral coverage of these objects down to 0.33 μm. The 25-filter data of 6 Hebe (Chapman and Gaffey, 1979; Gaffey, 1992, in preparation) were used to similarly scale and extend the 52-channel data of Hebe (Bell *et al.*, 1988). A broad shallow feature longwards of 1.6 μm is present in all three data sets. These spectra do not exhibit any well-defined 1 μm feature and certainly none that is of correspond-

TABLE 1. Observational circumstances.

Ast	Date	R.A.	Dec.	r(AU)	Δ(AU)	Mag.	β	λ	δ	Obs
387	85/05/04	11^h13^m	+24°54′	2.736	2.162	12.24	19°	159°	+18°	JFB
387	90/05/06	15^h23^m	+13°32′	2.308	1.384	10.70	13°	224°	+31°	MJG
980	85/12/24	6^h27^m	+33°02′	2.481	1.652	11.77	15°	53°	+15°	JFB

ing or greater intensity (depth) than the 2 μm feature, as is seen in 6 Hebe. The contrast between the 1 and 2 μm features in 387 Aquitania and 980 Anacostia and those of 6 Hebe emphasizes the anomalous nature of Aquitania and Anacostia. If the 2 μm features in Aquitania and Anacostia arose from pyroxene, one would expect a 1 μm feature at least as intense as that shown by Hebe.

A high resolution CCD spectrum of 387 Aquitania from 0.52–0.93 μm was obtained by Sawyer (1991) in his survey of mainbelt asteroids. In this wavelength interval, Aquitania has a linear spectral curve with a reddish slope and no evidence of any absorption feature near 1 μm. All other S-asteroids observed in that survey have an absorption feature longwards of approximately 0.8 μm. The slope of the CCD spectrum of Aquitania was the same as the ECAS data for that asteroid (Zellner *et al.*, 1985).

MINERALOGY OF AQUITANIA AND ANACOSTIA

None of the minerals which are commonly abundant in meteoritic assemblages—or any obvious combination thereof—will produce a spectrum in which the 2 μm feature is significantly stronger than the 1 μm feature. Orthopyroxene and clinopyroxene, which could readily produce a 2 μm feature, always have a 1 μm feature of equal or greater strength. Therefore, we considered less common meteoritic—or plausible asteroidal—minerals, whose abundance could be anomalously high in these asteroids or whose spectral contribution could be enhanced by some particle size effect or petrographic relationship. These include spinel, water ice, hydrated species, and organic materials.

Among the anhydrous minerals present in meteorites, spinel is the only species which we could identify that exhibits a spectrum with a strong 2 μm but no corresponding strong 1 μm feature (*e.g.*, Adams, 1975). The term "spinel" is ambiguous, since it can refer to a specific mineral (an aluminum-magnesium oxide mineral, $MgAl_2O_4$), to a suite of oxide minerals having the same structure as spinel (*e.g.*, magnetite and chromite are spinel group minerals), or to a type of crystallographic structure (*e.g.*, olivine converts to the spinel structure at high pressure). In the present paper we shall use the term "spinel" to mean the mineral spinel ($MgAl_2O_4$), which commonly incorporates small but spectrally important amounts of transition metal cations such as iron and chromium, which in the magnesium end member produce a bright red color similar to that of ruby.

Water ice and ice-rich mixtures (*e.g.*, Clark and Lucey, 1984) and water-rich mineral species such as hydrated salts (*e.g.*, Nash and Fanale, 1977; Crowley, 1991) can also exhibit absorption features in the 2 μm spectral region without a strong 1 μm feature being present. These features represent overtones and combinations of the fundamental vibrational modes (near 3 and 6 μm) of the water and/or OH molecule. However, there are several reasons to suppose that the 2 μm features in the spectra of Aquitania and Anacostia are not due to such hydrated species.

The presence of abundant water ice on the surface of either of these asteroids is highly unlikely due to the relatively high surface temperatures at their distance from the Sun. For an asteroid at a slightly greater heliocentric distance (*e.g.*, 1 Ceres at 2.77AU: Lebofsky *et al.*, 1981), it may be possible to have a thin frost layer on the sunlit hemisphere in the polar regions (if the rotational pole is nearly perpendicular to the orbital plane) or for a short period after local sunrise provided there is a sufficient source of water vapor to freeze out on the nightside. Even under those conditions, the resultant total water ice abundance on the illuminated surface would only be sufficient to produce a weak absorption at the 3 μm fundamental (*e.g.*, Lebofsky *et al.*, 1981) and is much too small to produce a significant absorption feature in the 2 μm region of the weaker overtones.

Hydrated mineral species (*e.g.*, salts, clay minerals, water-bearing organics) are somewhat better potential candidates because their water molecules are generally more tightly bound and can be retained at higher temperatures than water ice. However, the overtone features near 2 μm are relatively narrow, unlike the features seen in the spectra of Aquitania and Anacostia. The same situation is present in very thin frost layers, but at moderate grain sizes the wings of the individual water features (*e.g.*, 1.5, 2.0 and 2.5 μm) can intensify and produce a broad composite feature. For example, a broadly similar, if different in detail, feature is seen longwards of 1.4 μm in the spectrum of Callisto (Clark and McCord, 1980). This also occurs for hydrated species with reasonably high water contents or with large absorbance path lengths (*i.e.*, the product of the absorbing species abundance times the mean grain size).

For grain-size distributions which are typical of regoliths, clay minerals (King, 1986) or hydrated salts (Nash and Fanale, 1977; Crowley, 1991) do not commonly produce such a blended feature. Hydrated salts with sufficient water contents to produce such a feature are generally subject to significant dehydration in a vacuum at the peak surface temperatures present on these asteroids (Nash and Fanale, 1977).

The low albedos and the spectral features of most meteoritic organics (*e.g.*, Moroz *et al.*, 1991) are inconsistent with the spectrum and the relatively high albedo of these asteroids. However, irradiation of methane-bearing ices (*e.g.*, Thompson *et al.*, 1987) can produce organic compounds with moderate albedos that have a broad 2 μm absorption feature with no corresponding 1 μm feature (Cruikshank *et al.*, 1991). These features arise primarily from the blending of the vibrational features due to water and OH molecules included in the organic compounds. However, these organic compounds have very strong UV and visible absorptions which are not seen in the spectra of Aquitania and Anacostia. No plausible organic compounds so far considered can be simultaneously reconciled with the 2 μm feature and the UV-visible reflectance of these asteroids.

Thus, although some hydrated or organic species could in principle produce the 2 μm feature in the spectra of Aquitania and Anacostia, none investigated to date appear to be plausible candidates for the sources of these asteroidal features. Appropriate spectral data exist for only a small portion of the potential organic species, so this option cannot be foreclosed. However, this possibility can be tested observationally, since such a species would produce an intense 3 μm absorption feature in the spectra of such asteroids (*e.g.*, Jones *et al.*, 1990; Lebofsky *et al.*, 1990; Moroz *et al.*, 1991).

It also appears possible to rule out a shock origin for the 2 μm feature in Aquitania and Anacostia. Shocks associated with impacts can generate pressures and temperatures that produce exotic mineral species (*e.g.*, converting olivine to a spinel structure). However, the shocked meteoritic and mineral samples (*e.g.*, Gaffey, 1976; Bell and Keil, 1988; Britt *et al.*, 1989; King and Gaffey, 1992) tend to have subdued and relatively featureless reflectance spectra. No strongly enhanced 2 μm feature has been seen in the spectra of any of the shocked samples.

SEEING SPINEL IN ASTEROID SURFACES

We conclude that it is probable that the mineral spinel is largely responsible for the anomalous spectra of Aquitania and Anacostia. However, even though spinel is an important accessory mineral in the CV and CO meteorites, its physical abundance seldom exceeds a few percent. Under normal conditions, such a minor phase would be spectrally insignificant. Nor does it seem cosmochemically plausible that spinel could be a physically abundant mineral phase within the parent body(s) of Aquitania and Anacostia. It appears much more probable that the spectral contribution of spinel is due to either: (A) an enrichment of spinel within their parent body(s) by igneous processes at some internal layer which is present exposed on the surface of Aquitania and Anacostia, or (B) an abundance on the surfaces of Aquitania and Anacostia of spinel-bearing white inclusions similar to those in the CV3 meteorite Allende. Each of these is considered below.

Igneous Concentration of Spinels

The concentration of spinel by igneous processes is observed in terrestrial rocks. Extensive and economically important deposits of the spinel group minerals magnetite (Fe_3O_4) and chromite ($FeCr_2O_4$) have been formed by the settling of these dense phases (ρ = 5.18 and 4.6, respectively) to the bottoms of terrestrial magma chambers. When samples of a CV-type chondrite such as Allende are heated to 1200 °C, spinel and olivine are the two primary phases which remain solid in a melt of basaltic or angritic composition (*e.g.,* Jurewicz *et al.,* 1991). Since the mineral spinel ($MgAl_2O_4$) is denser (ρ = 3.5–4.1) than a basaltic melt (ρ = 2.8–2.9), the spinel can potentially segregate to the bottom of the molten silicate layer. In such a scenario, spinel could be highly concentrated near the core-mantle boundary. The presence of a spinel feature in the reddish spectra of Aquitania and/or Anacostia could therefore potentially be due to a spinel-bearing metal-rich assemblage. This is also an attractive hypothesis since the reddish spectral slope of S-asteroids is commonly ascribed to NiFe metal.

There are several reasons why we do not believe that the surfaces of Aquitania and Anacostia represent spinel-rich layers at a core-mantle boundary. Spinel is a minor phase in the Allende melts (a few percent: Jurewicz *et al.,* 1991) and would need to be efficiently segregated to produce a significant enrichment. The spectral contribution of spinel would be increased by a finer grain size. However, for a given mineral species the settling velocity (and hence, segregation efficiency) is inversely proportional to grain size (Stoke's Law), so that the spectrally desirable fine grained spinel would be unable to efficiently settle out of a silicate melt. A possible scenario would involve the growth and segregation of large spinel crystals with a subsequent exposure, fragmentation and dispersal of small spinel grains in a surface regolith.

The problem is complicated by the presence of low-iron olivine, another dense phase (ρ = 3.4–3.5) which will also tend to crystallize at high temperatures and to settle out of the basaltic melt. This olivine will be many times more abundant than spinel and the resulting residue or the cumulate assemblage will be dominated by olivine with spinel as a minor, if somewhat enriched, component. The olivine in such a cumulate layer will have a coarse grained plutonic texture, so that the reflectance spectrum of such an assemblage would have a strong olivine feature in addition to a spinel feature, unlike that seen in either of these asteroids. Pieters *et al.* (1990) show the spectrum of a lunar dunite (72415) with finely disseminated spinel which exhibits just such a spectral signature.

If a spinel-bearing, olivine-cumulate is comminuted by regolith processes, it is potentially possible to weaken the olivine spectral feature and to enhance (relatively) the spinel feature. However, the olivine feature is still strong in reflectance spectra of powders with particle sizes (<30 μm) which are much smaller than those expected in asteroid regoliths. To produce an isolated spinel feature similar to that seen in Aquitania and Anacostia from spinel-poor (≤10%) olivine-cumulate by fragmentation in a regolith would require mean particle sizes of less than 10 μm. This seems highly improbable.

At high degrees of partial melting where the olivine phase would not dilute the cumulate spinel deposit, the spinel tends to react with basaltic liquids and be consumed. Thus, while spinel is present as a very minor phase in most chondrites, it is absent from all achondrites except for the angrites which contain about 2% (Prinz *et al.,* 1977), which is consistent with their origin as relatively primitive melts (*e.g.,* Jurewicz *et al.,* 1991). However, the reflectance spectrum of an angrite (Angra dos Reis: Gaffey, 1976) is very strongly reddened, contains a strong 1 μm absorption band, and exhibits no detectable spinel feature, and hence does not resemble those of Aquitania or Anacostia. We could not identify a geochemically favored igneous pathway to create an assemblage that would produce spectra that showed spinel like that seen in Aquitania and Anacostia.

Spinel Features in Allende Inclusion Spectra

Figure 2 compared the reflectance spectrum of a spinel-bearing white inclusion in the Allende CV3 chondrite (Rajan and Gaffey, 1984; and in preparation) to the 0.8–2.6 μm reflectance spectra of Aquitania and Anacostia. The reflectance spectrum of the spinel-bearing inclusion exhibits a deep and broad absorption feature longwards of 1.3–1.5 μm due to spinel and a narrower and much weaker feature near 0.95 μm due (in this case) to pyroxene. Other spinel-bearing inclusions exhibit a weak olivine feature near 1.05 μm. Although the spinel is generally much less abundant than olivine and/or pyroxene in these inclusions (Kornacki and Wood, 1984a), the spinel feature in the spectra of these inclusions is much stronger than the mafic silicate features.

The strong enhancement of the spinel feature in the Allende white inclusions is due to two effects: the intensity of the spinel absorption, and the physical nature of the inclusions. Bivalent iron (Fe^{2+}) is the primary absorbing species in all three of these phases (olivine, pyroxene, spinel), and it is present in grossly similar abundances (5–30 mol%) in each. However the Fe^{2+} cations in olivine and pyroxene are in octahedral coordination sites while those in spinel reside in tetrahedral sites. The LaPorte-forbidden crystal field transitions in the octahedral sites (olivine, pyroxene) are much weaker than the LaPorte-allowed transitions in the tetrahedral sites (spinel). The reader is refered to Burns (1970) for a more detailed discussion.

Thus for an equivalent Fe^{2+} content, spinel produces a much

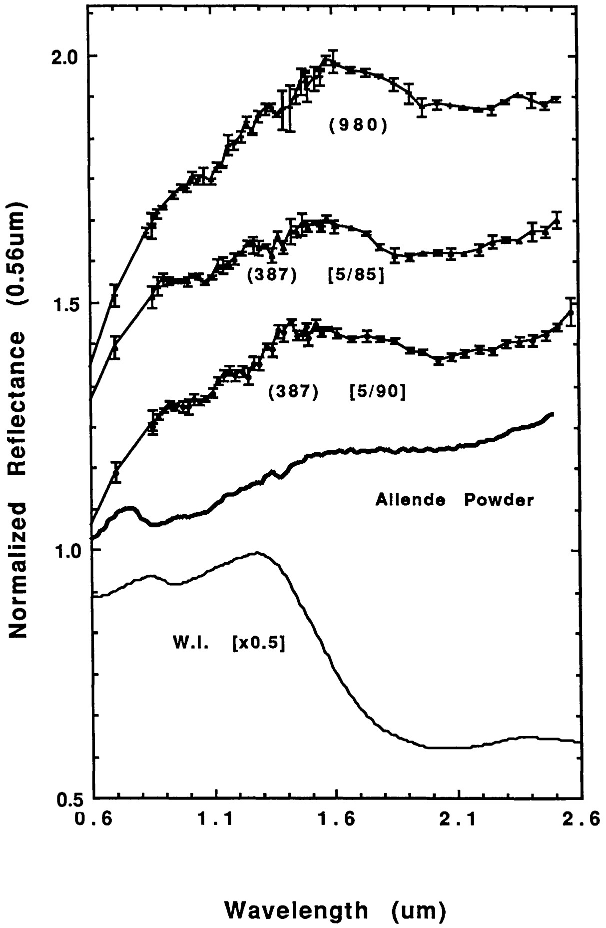

FIG. 2. The normalized reflectance spectra of 387 Aquitania and 980 Anacostia are compared to those of a bulk powder of the CV3 carbonaceous chondrite Allende (reflectance at 0.56 μm = 0.094) and and to a fine-grained spinel-bearing white inclusion (WI) from Allende (reflectance at 0.56 μm = 0.27). The white inclusion spectrum is vertically compressed by a factor of 2. All spectra have been normalized to unity at 0.56 μm, and the spectra of 387 [5/85] and 980 and of the Allende white inclusion have been offset for clarity by +0.30, +0.35 and −0.10, respectively. The strong 2 μm feature in the white inclusion spectrum is due to spinel. The broad shallow feature in the bulk Allende powder near 1 μm is due to olivine and pyroxene while that near 2 μm is due to pyroxene with a possible contribution from spinel.

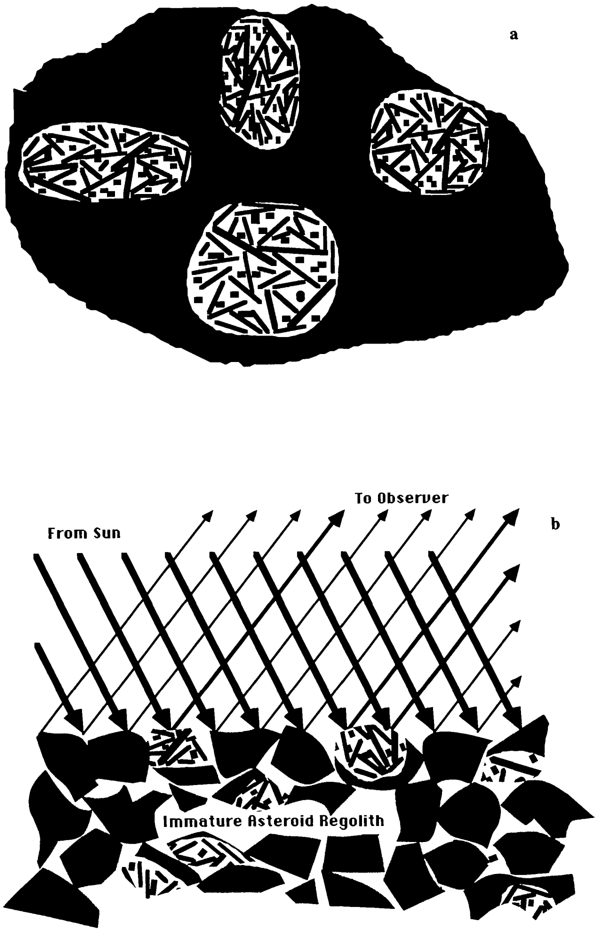

FIG. 3. (a) Schematic representation of the white inclusion-rich CV-type asteroidal substrate, analogous to the more inclusion-rich portions of the Allende CV3 chondrite. These white inclusions consist of relatively porous aggregates of transparent crystals, commonly resembling "bundles of straw," which scatter photons efficiently. The small stippled rectangles are intended to represent spinels, the only phase with significant absorption features over the visible and near-infrared spectral interval. The crystal size is typically on the order of a few microns. (b) A schematic representation of the incident and reflected fluxes from an immature regolith developed on an inclusion-rich CV-type substrate. In an immature regolith, the mean particle size is significantly larger than the crystal size within the white inclusions. In this situation, a photon striking a white inclusion fragment has a high probability of internal scattering and emission without encountering any dark matrix material. Photons striking a dark matrix grain are typically absorbed. The spectral flux contribution from the white inclusion fragments at a particular wavelength is equal to their abundance on the surface multiplied by a factor which is the ratio of the spectral albedos of the white inclusion and dark matrix at that wavelength.

more intense absorption feature. However, if the spinel is only present at the percent level in a mixture of meteoritic minerals with grain sizes typical of regoliths, this strong absorption will still be effectively suppressed. The presence of a strong spinel feature in the spectra of the Allende white inclusions is also due to the petrology of the white inclusions which provides a mechanism to strongly enhance the spectral signature of the minor spinel component.

The petrographic relationships in the white inclusions are shown schematically on Fig. 3a. These inclusions consist of relatively porous aggregates of fine-grained olivine, pyroxene, plagioclase, spinel and other oxide and silicate minerals. The crystal size is typically on the order of ten μm. Except for spinel, the mineral grains in the white inclusions are relatively transparent over the visible and near-infrared spectral interval either because they are very fine-grained (*e.g.,* olivine, pyroxene) or because they do not contain transition metal cations (*e.g.,* plagioclase, melilite). Photons are scattered efficiently at the crystal-void interfaces within the white inclusions until they either escape the inclusion or are absorbed, most commonly by the spinel component. This results in a high albedo compared to the dark matrix material in which they are enclosed. Since the photons have a long pathlength in the white inclusion, they have a high probability of encountering the only significant absorbing species, spinel, and exhibiting a spectrum dominated by that mineral phase.

EFFECTS OF REGOLITH PROPERTIES ON SPECTRAL REFLECTANCE

Lunar regolith processes significantly modify the spectral properties of the surface soil compared with those of the bedrock from which they are derived (*e.g.,* Adams and McCord, 1971). Due to the comparatively high escape velocity, ejecta from impact events are efficiently retained on the lunar surface and individual soil fragments are subjected to repeated fragmentation, shock, and melting events. On asteroid-sized bodies, the process of particle modification is expected to be terminated by the relatively early escape of the particle from the body. The most shocked and fragmented material is in the highest velocity ejecta. In the weak asteroidal gravitation fields, these are the least likely materials to be retained. Individual particles in asteroid regoliths are not expected to experience as many of the repeated impact events seen by those in the lunar regolith. The resulting asteroidal regoliths are expected to be relatively immature and composed primarily of coarse grained crystalline (*i.e.,* not highly shocked or melted) fragments of their substrates (*e.g.,* Matson *et al.,* 1977; Hörz and Schaal, 1981; McKay and Basu, 1983).

Thus, an asteroid surface regolith developed from a substrate composed of white inclusions in a dark matrix will have a mean particle size which is significantly larger than the crystal size within the white inclusions. In this situation, white inclusion fragments in the regolith will still consist of aggregates of numerous transparent crystals which scatter photons efficiently. By analogy, the fragments of a white snowball are still white so long as they are not too small and can still efficiently scatter light internally.

In an immature regolith, a photon striking a white inclusion fragment has a high probability of internal scattering and emission without encountering any dark matrix material. Photons striking a dark matrix grain are typically absorbed. The contribution of the white inclusions to the net flux at a given wavelength is proportional to their relative abundance multiplied by a factor equal to the ratio of the spectral albedos of the white inclusion and dark matrix at that wavelength. This is shown schematically on Fig. 3b. For example, in an immature regolith composed of 5% white inclusions and 95% Allende matrix, the white inclusions would contribute 15% of the reflected flux at 1.3 μm but only 5% at 2 μm. Extending the previous analogy, snowball fragments lying on a surface of loose dark clods will contribute disproportionately to the total reflectance (and reflectance spectrum) of the surface. This will continue to be true until the snowball (or white inclusion) fragments are either buried and hidden or broken down into sizes which allow most photons through to the surrounding and underlying dark material (*i.e.,* intimately mixed with comparable crystal/grain sizes as in a mature regolith).

There are significant differences between the spectra of Aquitania and Anacostia and between them and the spectrum of the Allende white inclusion shown on Fig. 2. The 2 μm feature of the Allende white inclusions is much more intense (approximately 10 times deeper in normalized spectra) and begins at a shorter wavelength than the feature in Aquitania and at a slightly longer wavelength than the feature in Anacostia. The difference in band intensity probably arises because such white inclusions are still only a relatively minor component in the surface assemblage of these asteroids. The different band edge positions could be due to differences in spinel chemistry. Mao and Bell (1975) assign the strong spinel absorption feature near 2 μm (with an edge near 1.5 μm) to Fe^{2+}, and a somewhat weaker (in their sample) spinel feature near 1.3 μm (with an edge near 1.25 μm) to Cr^{2+}. The difference between the Aquitania and Anacostia features is within the range of variation observed by Mao and Bell (1975), but the detailed analysis of such asteroid spectra is hindered by the paucity of spectral data on different types of spinel.

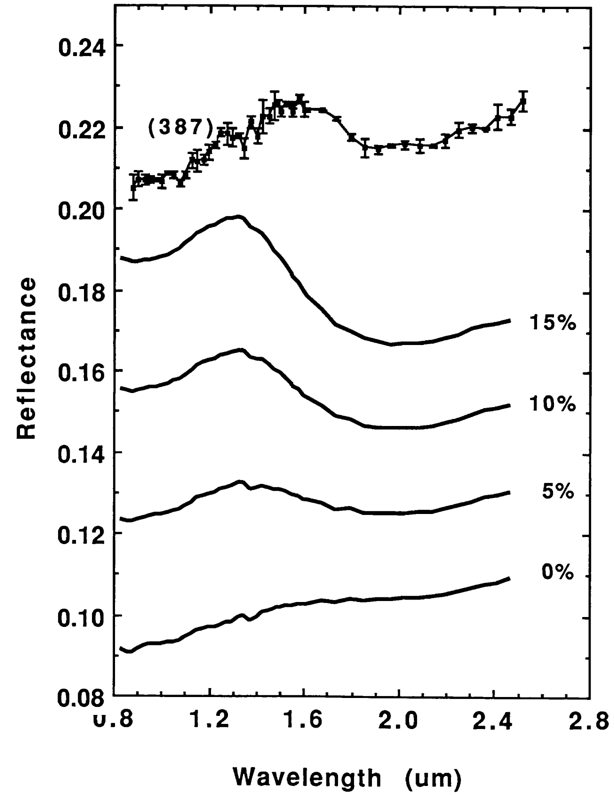

FIG. 4. The reflectance spectrum of 387 Aquitania compared with simple linear spectral mixing model of mixtures of a white inclusion component into an Allende-type CV3 matrix (an average of Allende and Mokoia). The fractional abundance of the white inclusion and CV3 matrix is indicated for each mixture. The Aquitania band intensity is best matched by a spinel-bearing white inclusion abundance of slightly more than 5% while Anacostia suggests an abundance nearer 10%. The longer wavelength position of the short wavelength absorption edge of Aquitania relative to the simulation may arise because of different spinel compositions. For clarity, the spectra of the 5%, 10% and 15% mixtures are offset by +0.02, +0.04 and +0.06, respectively.

Assuming that the Allende white inclusions are an appropriate analog and that the surface regolith of these asteroids is relatively immature, we have used a simple linear mixing model to estimate the abundance of such a white inclusion component on the surfaces of Aquitania and Anacostia. Figure 4 compares the spectrum of Aquitania to a simple additive spectral mixture (checkerboard model) of a white inclusion component into an Allende-type CV3 matrix. The Aquitania band intensity is best matched by a spinel-bearing white inclusion abundance of slightly more than 5% while Anacostia suggests an abundance nearer 10%. These estimates are substantially higher than their actual abundance in Allende (Kornacki and Wood, 1984a), although

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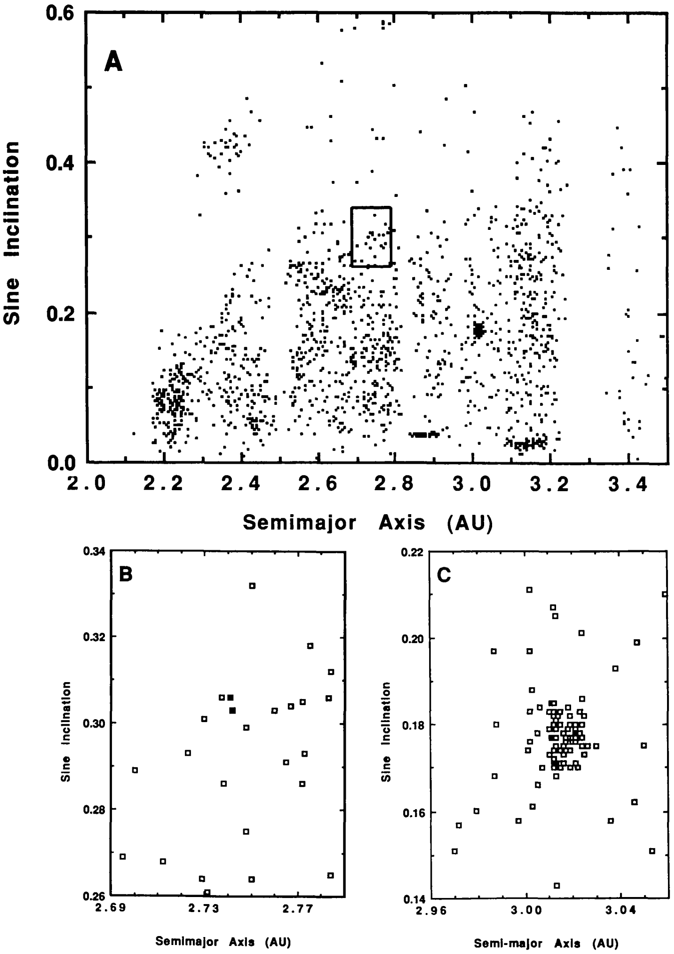

FIG. 5a. A plot of proper semimajor axis versus proper sine of inclination for nearly 1800 asteroids from the compilation of Williams (1989). The small rectangle centered near a = 2.74 AU and sin(i) = 0.3 includes asteroids 387 Aquitania and 980 Anacostia.

FIG. 5b. An expanded view of the region which includes Aquitania and Anacostia which are indicated by the solid squares.

FIG. 5c. The region of the Eos family at the same expanded scale as Fig. 5b, above. Note that the distance (in proper element space) between Aquitania and Anacostia on Fig. 5b is comparable to or smaller than the typical distances between members of the well defined Eos family.

there is considerable variation in their abundance between different portions of Allende.

The anomalous spectra of 387 Aquitania and 980 Anacostia can therefore be explained by a reasonable variation on known meteoritic assemblages (*i.e.*, a white inclusion rich CV3) undergoing modeled asteroidal regolith processes. It is generally believed that the white inclusions are a relatively early nebular product. It is also observed that their abundance varies by nearly two orders of magnitude between different CV3 and CO3 meteorite specimens, and that their abundance in other chondritic meteorites is generally well below that in the CV/CO group. We suggest that these asteroids formed in the same general region of the solar nebula as the CV3 chondrites but that they either accreted at a stage in nebular evolution when such white inclusions were a larger fraction of the nebular grain population or at a particular location in the nebula where such spinel-bearing inclusions had been concentrated.

Although present understanding of nebular events is meager, the processes involved may have been similar to those invoked to explain some elemental fractionations in meteorites (*e.g.*, Grossman and Wasson, 1982; Larimer, 1988), in which larger (*e.g.*, the white inclusions) or early formed grains cannot be supported by convective motions and settle to the nebular midplane (*e.g.*, Weidenschilling, 1988). The formation temperatures of the Allende dark matrix are several hundred degrees lower than those of the spinel-bearing white inclusions (*e.g.*, Grossman and Larimer, 1974; Kornacki and Wood, 1984b). The cooling time of plausible nebular models through such a temperature interval is longer than the time scale (10^2–10^3 years: Weidenschilling, 1988) to segregate cm-sized grains to the midplane where they could undergo accretion into early planetesimals. The existence of similar white inclusion-rich parent bodies has been invoked to produce the chondritic parental material of the angrite meteorites (*e.g.*, Delaney and Sutton, 1988).

It has been suggested that the K-class asteroids are also related to the CV/CO chondrites (Bell, 1988). Aquitania and Anacostia would differ from that interpretation of the K-class in their higher abundance of the spinel-bearing white inclusions.

ORBITS

The similarity of the orbital elements (Table 2) of these two asteroids raises the possibility that they may be genetically related and either: A) have a common origin in a single disrupted parent body, or B) represent objects which both accreted from a nebular zone which was highly enriched in spinel-bearing white inclusions. Figure 5a is a plot of proper semi-major axis versus proper sine of inclination for nearly 1800 asteroids from the proper element tabulation of Williams (1989). Figure 6a is a similar plot for the proper elements of about 4500 asteroids computed by a different procedure (Knezevic and Milani, 1989; version 5.7, updated 91/04/24). Aquitania and Anacostia are located within the small boxes centered upon their positions on Figs. 5a and 6a. An expanded view of this region is shown on Figs. 5b and 6b with Aquitania and Anacostia as solid squares. For comparison, the region of the Eos family is shown at the same expanded scale on Figs. 5c and 6c. The asteroids in the Eos family are believed to be genetically related (fragments of a disrupted parent object) by almost all asteroid researchers (Chapman *et al.*, 1989). For purposes of the present study, both sets of proper elements result in the same conclusions.

Asteroid families have been historically defined solely on the basis of dynamical criteria (*i.e.*, clumps in orbital element space—a, e, and i). However, there is a growing consensus that distinguishes "true" genetic families from dynamical associations without proven genetic relationships (Bell, 1989; Chapman *et al.*, 1989; Farinella *et al.*, 1992).

Although there is no dynamical basis for expecting the dispersion in inclination to be less than that in eccentricity, Aquitania and Anacostia have proper semi-major axes and proper inclinations with differences comparablre to those within the Eos family and which are much closer to each other than would be expected from random chance. What are the odds that two objects with very similar spectra could have such similar orbital elements by chance? More specifically, among the asteroids sampled in the 52-channel survey, how probable is it that any two asteroids would have such similar orbital elements? The probability of any random 52-channel survey object being located within the observed proper "a" and proper sine "i" distance was evaluated based upon a statistical analysis of the distribution of differences in orbital elements between three thousand random pairs of asteroids from Knezevic and Milani (1989; version 5.7, updated 91/04/24). The probability of any two random asteroids within the 52-channel survey set having orbital element ("a" and "i") differences equal to or less than the Aquitania-Anacostia pair is approximately 0.0006. Since they were initially paired based upon spectral criteria which were independent of their orbits, their orbital proximity suggests that they may indeed be dynamically related. The next closest member of the 52-color survey in this proper element set (532 Herculina) is nearly ten times further away and bears no spectral resemblance.

Assuming that Aquitania and Anacostia are both genetically and dynamically related, can we distinguish between an accretional origin (*i.e.*, both formed from the same nebula zone) and a collisional origin (*i.e.*, both are members of a partially dispersed asteroid family from the breakup of a single parent body)? Nebular accretion of condensed matter into planetesimals is generally believed to have taken place primarily within a planar disk of dust and grains which had settled out of the nebula into the central plane. These initial planetesimals would have had circular coplanar (*i.e.*, inclination = 0°) orbits. If Aquitania and Anacostia were formed separately in a zone of white inclusion enrichment within this disk, then the inclinations of both would have to have been independently raised to their present very similar values. This seems much less probable than the hypothesis that the present inclinations and semi-major axes represent that of a common parent body which was disrupted after its inclination had been raised to near 18°.

Could Aquitania and Anacostia be fragments of a disrupted parent body? There is no obvious concentration of objects in proper element space (Figs. 5 and 6) associated with these asteroids, and they would not be identified by the present methods to identify families because their eccentricities are significantly different (*e.g.*, Valsecchi *et al.*, 1989; Zappala *et al.*, 1990; Williams, 1992). Aquitania and Anacostia may be members of what Granahan and Bell (1992) termed "partially dispersed families," which have concentrations in semi-major axis and inclination but are dispersed in eccentricity. Granahan and Bell (1992) suggested that these might represent an older generation of "families," now largely dispersed. The different eccentricities of the Aquitania-Anacostia pair may simply result from the earlier breakup of their parent body than that of the Eos family.

Besides being spectrally anomalous, both Aquitania and Anacostia have rotation periods (Table 2) that are significantly longer than most asteroids or most members of the S-class of similar sizes (approximately 12 hours at 100 km diameter: Binzel *et al.*, 1989). Binzel (1988) suggested that the rotation rates of the largest members of the Eos and Koronis families may be similar to that of their original parent bodies, so that the similarly long periods of Aquitania and Anacostia may result from a common slowly rotating parent body. Alternately, Cellino *et al.* (1990) noted that catastrophic disruption of an asteroid parent body would produce anomalously long rotation periods in the 80–120 km size range, and the rotation rates of these two asteroids may reflect such an event.

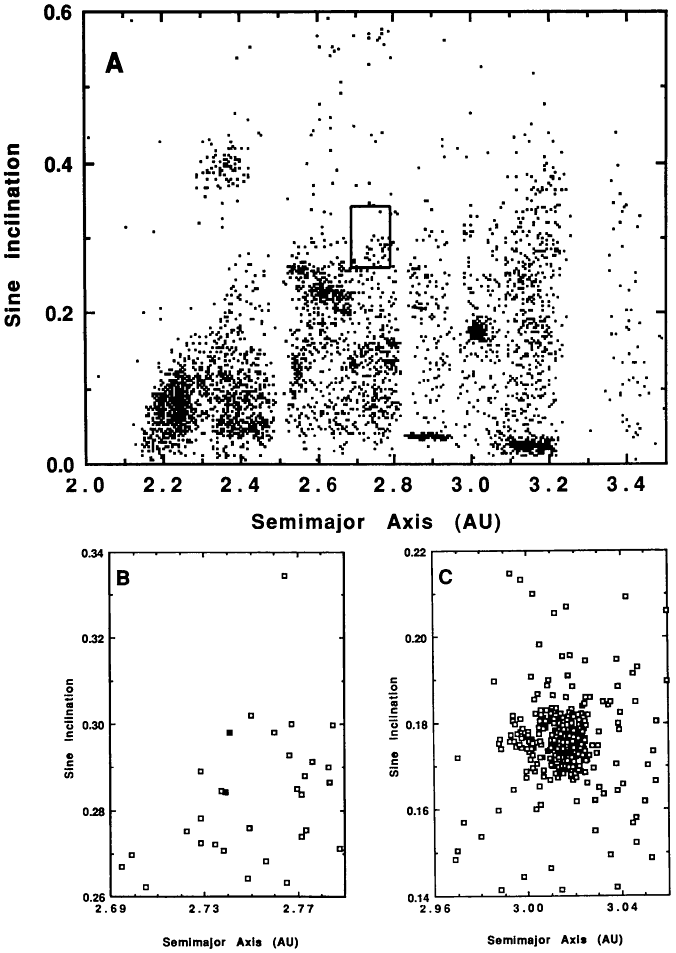

FIG. 6. Similar to Fig. 5 but from the proper elements of 4500 asteroids computed by the procedure of Knezevic and Milani (1989; version 5.7, updated 91/04/24).

Are There Other Members of the Postulated Family?

It seems plausible that if the Aquitania-Anacostia pair are two members of a partially dispersed family produced by the disruption of a spinel-bearing CV3-type parent body, then other members of such a family should also be spectrally distinct. If the orbital elements of other members have been changed too drastically, any association would be very difficult to prove. And obviously any members which have been completely disrupted by subsequent collisions cannot be observed since they no longer exist. However, the existence of a moderately dispersed family of spectrally distinct objects can be tested by spectral examination of the nearby objects.

Among previously classified asteroids, which other objects are potential candidates for membership in such an Aquitania-Anacostia family? Two asteroids, 599 Luisa and 729 Watsonia (Table 3), appear to be the most obvious initial candidates. Both Luisa and Watsonia have very similar orbital elements to Aquitania and Anacostia. Luisa is classified as an S in Tholen's (1984) original classification based upon its ECAS spectrum. Luisa and Aquitania have very similar ECAS spectra as indicated by the nearly identical principal component scores of Luisa

Table 3. Physical and orbital properties.

	599 Luisa		729 Watsonia	
Tholen class[a]	S		STGD	
Proper orbital elements				
Semimajor axis (AU)	2.772[b]	2.773[c]	2.760[b]	2.760[c]
Sine of inclination	0.305	0.288	0.303	0.298
Eccentricity	0.209	0.227	0.113	0.124
IRAS albedo[d]	0.14 ± 0.01		0.11 ± 0.01	
IRAS diameter[d]	69.6 ± 1.7 km		53.5 ± 2.7 km	
Rotation period	9.566 ± 0.013 hours[e]		—	

a) Tholen, 1989; b) Williams, 1989; c) Knezevic and Milani, 1989—version 5.7, updated 91/04/24; d) Tedesco, 1989; e) Debehogne *et al.*, 1977.

(3.436,0.563) and Aquitania (3.511,0.566) (Tholen, 1984). Watsonia, which was not classified in Tholen's original classification, is classified with the ambiguous designation of STGD by Tholen (1989) based solely on UBV colors. This classification would put Watsonia in the same region of Tholen's principal component diagram as Aquitania and Anacostia. However, it is impossible to test the possible genetic link of an asteroid with the potential Aquitania-Anacostia family without the near-infrared spectra (to 2.5 μm) for that object.

CONCLUSIONS

The reflectance spectra of asteroids 387 Aquitania and 980 Anacostia are anomalous for the S-class. They exhibit a strong broad absorption feature longwards of 1.5 μm and no significant feature near 1 μm. Their spectra are most probably produced by spinel, an aluminum-magnesium oxide mineral commonly present in inclusions in CV3 and CO3 meteorites, and less commonly in other chondritic types. Spinel constitutes only a small portion of the surface assemblages of these asteroids, but its spectral effect is enhanced by its presence in fine grained white inclusions in immature asteroid regoliths. It seems plausible that Aquitania and Anacostia represent material formed in the same nebular zone as the CV3 and CO3 chondrites but either: A) at an earlier time in the nebular cooling sequence when such inclusions would have constituted a relatively higher proportion of the nebular grain population, or B) in local regions where nebular processes (such as settling to the midplane) had concentrated such inclusions.

The close similarity of the two orbital elements (a, i) suggests that Aquitania and Anacostia may be members of a partially dispersed asteroid family produced by the disruption of their common spinel-bearing parent body. Since there is no significant concentration of objects in orbits similar to these two asteroids, it is suggested that the disruption of the parent took place significantly prior to those of the parent bodies of the Eos, Koronis, and other well defined families. In such a model, most original members of the postulated Aquitania-Anacostia "family" would have been destroyed or would have diffused into the background population. Spectral studies out to 2.5 μm would be the only direct means of identifying such strayed family members.

This is the first time that a potential asteroid genetic family has been suggested on the basis of spectral data and orbital data in combination. Spectral studies of other groupings in the more robust proper elements may be able to distinguish other old, partly dispersed families.

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