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Preliminary analysis of an expanded corona database for Venus

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Abstract. We have conducted an extensive survey of the Magellan data to reassess the population of coronae. We identify a new type of coronae, here referred to as 'Type 2 coronae', having the same basic morphology as previously identified coronae (Type 1), but lacking a significant (>50%) annulus of closely spaced fractures. 106 Type 2 coronae are included in the new database giving a total of 515 coronae on Venus. The characteristics of the expanded population of Type 1 coronae are similar to those of the previously described population, but the Type 2 coronae are smaller, tend to have relatively flat interiors surrounded by a topographic rim, and are more likely to be found isolated from other features. Our observations, in particular the morphology and setting of the Type 2 coronae, may provide supporting evidence for the existence of a depleted mantle layer under the venusian plains.

Introduction

Coronae are large-scale volcano-tectonic structures first described by Barsukov *et al.* [1984], that are widely considered to be the surface manifestation of mantle upwelling [Basilevsky *et al.*, 1986; Stofan *et al.*, 1991; Janes *et al.*, 1992]. They are approximately circular structures that range in diameter from 60 km to over 1000 km. Nearly all coronae have associated volcanic and tectonic features, including large numbers of small (< 50 km diameter) volcanoes, extensive flow deposits, radial fractures, and concentric fractures and ridges [Solomon *et al.*, 1992; Squyres *et al.*, 1992; Stofan *et al.*, 1992; Roberts and Head, 1993; Stofan *et al.*, 1997].

Coronae typically have a raised rim superimposed on which is an annulus of closely spaced concentric fractures and/or ridges. It is this annulus of fractures that is clearly delineated in the Magellan radar images. Stofan *et al.* [1992] applied a definition that the annulus surrounding a coronae must be greater than 180° of arc for the feature to be classified as a corona. Utilizing this definition and Magellan image data only, they identified 336 coronae and 26 'corona-like' features in the approximately 80% of the planet that had been imaged by 1992.

We have conducted a new survey of coronae using the complete Magellan image and topography data sets, identifying two types of coronae. Type 1 coronae are >50% (180° of arc) surrounded by closely spaced, concentric fractures, and are the basic type in the Stofan *et al.* [1992] survey. This survey of coronae includes a new type of corona, Type 2 coronae, most of which have topographic rims, but have less than 180° of arc of fracturing and often have no concentric fracturing at all (Figure 1). Due to the lack of a significant fracture annulus, Type 2 coronae are difficult to detect in the Magellan radar images alone, and hence were originally referred to as 'stealth coronae' [Tapper, 1997]. However, most Type 2 features have a clear topographic rim, as with Type 1 coronae. In this study, we have identified 515 Type 1 and 2 coronae, whose location and diameter are listed in the new database (http://webgis.wr.usgs.gov/venus_general.htm). In the new survey, we eliminated the category of 'corona-like' features, as they lack a defined ridge/fracture or topographic annulus and most have been reclassified as volcanoes.

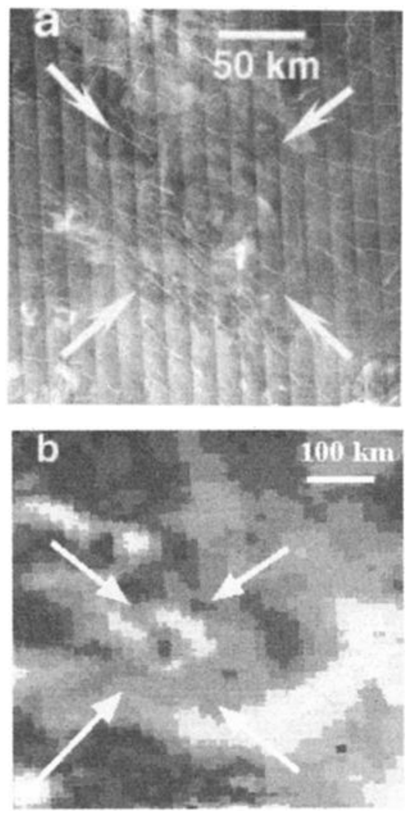

Figure 1. Magellan radar image (a, C1-MIDR 15N163) and topographic image (b, Magellan Global Altimetry data, Mercator projection) of a Type 2 corona located at 16.3°N, 163.6° (arrows point out feature in both images). The diameter of the feature is 127 km. Only a faint suggestion of the topographic rim can be seen in the radar image, though some of the regional wrinkle ridges are deflected around the feature. The topographic image indicates that the feature is in the rim only group, with the rim raised < 500 m above the surrounding terrain.

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Table 1. Corona Topography

	1992 Survey Coronae	Type 1 Coronae	Type 2 Coronae
1- Domes	10%	7%	0%
2- Plateaus	10%	13%	7%
3a- Rimmed plateaus	8%	9%	6%
3b- Rims with central high	13%	16%	4%
4- Rimmed depressions	25%	28%	23%
5- Outer rise, trough, inner high	5%	5%	0%
6- Outer rise, trough, inner low	1%	1%	0%
7- Rim only	7%	8%	54%
8- Depressions	7%	10%	4%
9- No apparent signature	14%	3%	2%
Total	100%	100%	100%

The large increase in the number of coronae over the 1992 survey results from several factors. For the new survey, we utilized the final set of Magellan data that covers over 98% of the surface of Venus. Data sets used include Magellan altimetry data, synthetic aperture radar (SAR) images, and synthetic stereo images created by the U.S. Geological Survey. The use of the topography data in conjunction with the image data, which was not done in the original survey, greatly increased the number of features. Also, additional coronae have been identified as part of the systematic geologic mapping of Venus (http://wwwflag.wr.usgs.gov/USGSFlag/Space/nomen/).

Here we document the general characteristics of the expanded corona population. We describe the morphology of Type 2 coronae, including their tectonic and volcanic characteristics, and their size distribution. We compare Type 1 and 2 coronae, and assess the implications of the expanded corona population.

Morphology

Stofan *et al.* [1992] classified the corona population into five classes, based primarily on the nature of the corona fracture annulus. These classes are concentric, concentric/radial, asymmetric, concentric-double-ring and multiple. We have classified the additional Type 1 coronae identified in this survey into the same classes; the Type 2 coronae lack enough fracturing to be classified. As with the original population, approximately half of the new Type 1 coronae are in the concentric class, with symmetric, well-defined annuli. Asymmetric is the next most common class. Less than ten new radial/concentric and concentric-double ring coronae were found. No new multiple coronae were identified.

Corona topography is classified into 9 categories, with category 3 broken into two subcategories (Table 1, and see Table 1 in Smrekar and Stofan [1997]). The original 1992 population and the expanded Type 1 population have relatively similar topographic groupings (Table 1), which is not surprising, given that most of the 1992 survey features are included in the new Type 1 population. The 1992 survey had 46% topographically raised features (categories 1, 2, 3 and 5) and 33% depressions (categories 4, 6 and 8). For the 409 Type 1 coronae, 50% are raised topographically and 39% are depressions.

The Type 2 coronae fall into almost the same topographic groups as Type 1 coronae. However, the distributions between the topographic groups are quite different. Only 17% of Type 2 coronae are raised features, with 27% depressions. In addition, 54% of Type 2 coronae are classified as rim only, as compared to 8% of Type 1 coronae. The 4% of Type 2 coronae that are depressions without raised rims could also be completely flooded impact craters.

The expanded population of coronae did not exhibit any major differences in tectonic or volcanic characteristics as compared to the 1992 survey population. All coronae, including all but 9% of Type 2 coronae, have some associated deformation, typically some concentric fractures. At Type 2 coronae, concentric fractures typically surround less than 30% (~110° of arc) of the feature. Where concentric fractures are present at Type 2 coronae, they either surround the topographic rim (11%), lie inside the topographic rim (3%) or on the topographic rim (32%). Thirty-nine percent only have associated deformation outside the topographic rim; most of these are wrinkle ridges that have been apparently deflected by the corona. Nearly all coronae have associated volcanism; no Type 2 coronae have the extensive flow fields associated with some Type 1 coronae (e.g., as described by Roberts and Head [1993]).

Dimensions

As with the 1992 survey, we used the fracture annulus extent to define width. Where no fracture annulus was present, we measured the outermost extent of the topographic rim to define width. The maximum widths of asymmetric or elliptical coronae are used in this analysis. In our analysis of corona dimensions, we did not include Artemis Corona. With a diameter of approximately 2600 km, it is significantly larger than the next largest corona (Heng-o, 1060 km diameter), and may have formed by a different mechanism [Brown and Grimm, 1995].

The population of Type 1 coronae, as with the 1992 corona survey, tends to have maximum widths between 200 and 300 km (Figure 2). The 1992 survey population had a mean of 275 km and a median of 230 km [Stofan *et al.*, 1992]; the new population of Type 1 coronae has a mean of 258 km and a median of 215 km, with a standard deviation of 152 km. Chi-squared analysis of the population indicates that the distribution of Type 1 corona widths is a classic lognormal population [Stofan *et al.*, 2001].

Type 2 coronae also tend to have maximum widths from 200-300 km, with a minimum of 73 km and a maximum of 700 km. Like Type 1 coronae, the size distribution of Type 2 coronae is lognormal, also supported by χ^2 analysis [Stofan *et al.*, 2001]. However, Type 2 coronae tend to be smaller, with a mean of 239 km and a median of 206 km, and a standard deviation of 127 km.

Distribution and Geologic Setting

Stofan et al. [1992] found, plotting coronae in equal area latitude bins, that there are greater concentrations of coronae at mid-latitudes, and that coronae tend to occur in clusters. Squyres et al. [1993] determined that the distribution of coronae is non-random, with the highest concentration in the Beta-Atla-Themis region (between approximately 30°N-45°S latitude, 210°-280°E longitude). The new population of coronae appears to show a slightly higher concentration at higher latitudes. There is noticeable clustering in longitude of coronae between

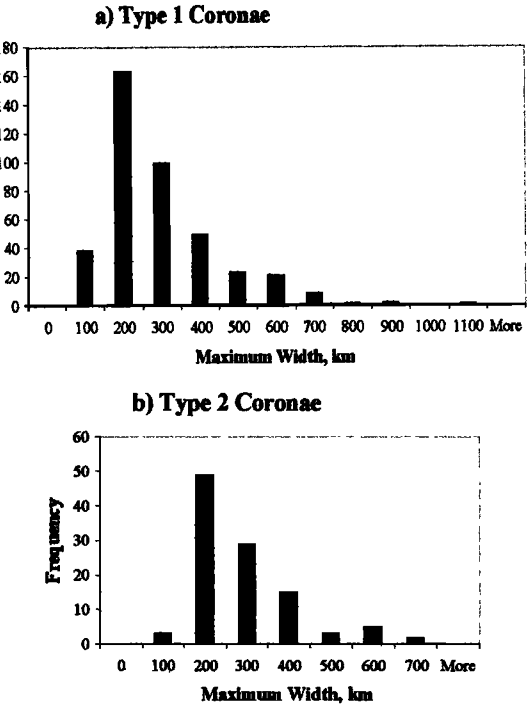

Figure 2. Histograms of the size distribution of (a) Type 1 and (b) Type 2 coronae.

approximately 0°-50°E longitude, as well as the previously identified Beta-Atla-Themis clustering. There is also a deficit of coronae between 100°-200° longitude.

Coronae are found in three geologic settings; on volcanic rises, along chasmata/fracture belts, and in isolation from other types of geologic features (i.e., fracture belts, ridge belts, tessera) in the plains [Stofan *et al*, 1997]. Coronae identified by the new survey are found in each of these settings. Most coronae identified by Stofan *et al.* [1997] were found along chasmata or fracture belts (68%). For the new group of Type 1 coronae, 68% were located along fracture belts or chasmata, 18% isolated features and 13% at hotspot rises. For Type 2 coronae, 43% were found at fracture belts and only 2% at hotspot rises. The most striking difference between the two surveys however is that Type 2 coronae are preferentially located as isolated features in the plains (56%).

Discussion

Implications of Type 2 Coronae.

Copp *et al.* [1998] described coronae as having two scales of annular deformation: a topographic rim and an annulus of ridges and/or fractures. Here, we have described Type 2 coronae which have a topographic rim, but either entirely lack annular fracturing or have only partial fracture annuli. At Type 2 coronae that are depressions (4% of the population), rim fractures may have been covered by volcanic flows. However, most Type 2 coronae have topographically raised rims that dominantly lack fracturing. The observation that some coronae have a topographic rim but do not have a well-developed deformational annulus suggests that either not all coronae form complete annuli, or that these coronae have yet to develop a fracture annulus. However, the range of topographic forms found among Type 2 coronae is representative of all stages of corona development put forward by Smrekar and Stofan [1997], indicating that the evolutionary stage of these coronae is likely to be quite broad.

In the absence of plate recycling, it is hypothesized that a low density, depleted mantle layer can form the lower part of the lithosphere [Parmentier and Hess, 1992]. Smrekar and Stofan [1997] modeled the formation of coronae from an upwelling with and without the presence of a depleted mantle layer. They found that interior lows form when a plume thins a substantial depleted mantle layer. Rim only coronae were produced only through a combination of delamination and rebound of a depleted mantle layer. Smrekar and Stofan [1997] found a higher percentage of these features in the venusian plains, leading them to postulate the presence of a depleted mantle layer underlying the plains. As described above, Type 2 coronae are much more commonly found as isolated features in the plains than Type 1 coronae, and over half have a rim only topographic form. We interpret this to indicate that the formation of coronae lacking a well-defined fracture annulus is favored in the presence of a depleted mantle layer.

The lack of a fracture annulus coincident with the topographic rim at Type 2 coronae could be caused by several factors: 1) a purely ductile lithosphere due to high heat flux; 2) a very strong lithosphere and thus low stress at the surface; and 3) slow viscous bending (low strain rate). We do not favor option (1), as unrealistically high values of heat flux would be needed to move the brittle-ductile transition to the surface. We favor option (3), lower strain rates, as the most probable cause of the lack of a fracture annulus. This hypothesis is consistent with isostatic rebound of a depleted mantle layer, or possibly of a thickened crustal layer after delamination has ceased. Low strain rates are inferred due to the strength of the venusian lithosphere [Johnson and Sandwell, 1994; Phillips et al., 1997; Mackwell et al., 1998] and the low rim heights of all coronae. Further gravity studies of Type 2 coronae are consistent with this hypothesis; Smrekar and Stofan [2001] found that many Type 2 coronae with depressed interiors are bottom loaded, suggesting isostatic rebound with associated low strain rates. Other Type 2 coronae with depressed interiors may be crustally compensated. The majority of rim only coronae also have either a bottom loaded signature or a possible crustal compensation signature. However, option (2), strong lithosphere, may also be important. We are in the process of comparing the rim heights and widths of Type 1 and Type 2 coronae. We would expect rims without fractures to have less curvature if option (2) is true, and rims without fractures to be lower if option (3) is the most significant factor.

Implications of a Larger Coronae Population

A greater number of coronae have implications for heat loss modeling. Smrekar and Stofan [1997] used their model of corona formation to calculate a buoyancy flux for coronae of 92 Mg/s. This was based on the fact that approximately half of coronae have raised topography and thus are likely to still be active, with about one quarter of coronae (those with raised interiors) supported by active plumes and about one quarter (raised coronae with outer rims) characterized by both a plume and ongoing delamination. To estimate the overall contribution to heat loss on Venus, the buoyancy flux for coronae was scaled using the estimated value of approximately 50 Mg/s for terrestrial hotspot heat loss [Davies, 1988; Sleep 1990], which was estimated to be 10% of the total terrestrial flux [Davies, 1988].

To re-estimate the contribution of all coronae to heat loss on Venus, we multiply the corona buoyancy flux by C/α, where C is the specific heat per mass (1.25×10^{3} J/kg°C) and α is the coefficient of thermal expansion (3×10^{-5}°C^{-1}) [Sleep, 1990]. This value is then averaged over the surface of the planet. This direct calculation of heat flux is preferable to scaling to the terrestrial value of hotspot heat loss, as it eliminates any uncertainty associated with this value. Our new database has 89 topographically raised coronae that may be underlain by active plumes, and 115 coronae with topographic rims that are most likely to be undergoing active delamination combined with an active plume. Using values for buoyancy flux at coronae with and without active delamination [Smrekar and Stofan, 1997], we can calculate a corona buoyancy flux estimate using 89 coronae x 0.30 Mg/s = 26.7 Mg/s and 115 coronae x 0.72 Mg/s = 82.8 Mg/s, for an overall corona buoyancy flux of 109.5 Mg/s. When multiplied by C/α and averaged over the planet, this method gives a value of 9.92 mW/m^2. Typical parameterized convection solutions for stagnant and non-stagnant lid regimes range from 35-50 mW/m^2 for heat loss on Venus [Phillips *et al.*, 1997]. This suggests that coronae could represent 20-28% of present day heat loss.

Conclusions

We have expanded the original Stofan *et al.* [1992] database of 336 coronae to 514 coronae using the global Magellan data sets. The large numbers of additional coronae identified suggest that coronae might contribute 15-28% of the heat loss of Venus. We have now termed coronae with fracture annuli 'Type 1' coronae.

We have identified a significant number of additional coronae that have a topographic rim, but lack a fracture annulus. We find that most occur as isolated features in the plains. These coronae, termed Type 2 coronae, are somewhat smaller than Type 1 coronae and typically consist of a relatively flat interior surrounded by a raised rim.

The concentration of Type 2 coronae as isolated features in the plains and their topographic forms are consistent with preferential formation in the presence of a thickened, chemically depleted mantle layer. The lack of a tectonic annulus at Type 2 coronae is also consistent with formation of these features in regions of depleted mantle, with corona formation characterized by slow bending of the surface. We are in the process of analyzing the gravity signatures of Type 2 coronae, in order to further understand the relationship between corona morphology and lithospheric structure [Comstock *et al.*, 2001; Smrekar and Stofan, 2001].

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