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Title: Imaging of a Circumsolar Dust Ring Near the Orbit of Venus

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Abstract:

The gravitational interaction of dust in the zodiacal cloud with individual planets is expected to give rise to ring-like features: such a circumsolar ring has been observed associated with the Earth, but such resonance rings have not been confirmed to exist for other planets. Here we report on sensitive photometric observations, based on imaging from the STEREO mission, that confirm the existence of a dust ring at the orbit of Venus. The maximum over-density of dust in this ring, compared to the zodiacal cloud, is $\approx 10\%$. The radial density profile of this ring differs from the model used to describe the Earth's ring in that it has two distinct step-like components, with one step being interior, and the other, exterior, to the orbit of Venus.

Main Text:

A circumsolar dust ring is known to exist around the orbit of the Earth (1,2). It arises from the trapping of interplanetary dust grains, primarily of asteroidal and cometary origin (3-5), into orbits that are resonant with the Earth's orbit. Dust grains of size 1-100 μm are subject to Poynting-Robertson (P-R) drag, and to a lesser extent, solar wind drag, which results in a gradual decay of their orbits (about 10^4 years for a 10 μm particle at 1 AU) (6). As a dust grain slowly spirals inwards towards the orbit of the Earth, it successively passes into locations in which it may be trapped temporarily (for timescales of 10^4 to 10^5 years) into a particular orbital resonance (1, 7-9). Dust in individual resonances will cluster into periodic patterns around the orbit, and when multiple resonances combine to form a real dust ring, these underlying structures result in the azimuthal distribution of the ring being non-uniform (1).

Searches for resonance structures around the orbits of Mars and Jupiter have not yet been successful (10). The situation at Venus is more complex. A detection of enhanced scattering was reported (11) from *Venera* 9 and 10, but is attributed to circumplanetary rather than circumsolar dust. Based on a re-analysis of photometry from the *Helios* mission, data consistent with a dust ring just outside the orbit of Venus has been presented (12) but the existence of such a ring could not be confirmed beyond doubt.

A circumsolar dust ring at Venus would provide observational data which should lead to improved understanding of the factors affecting the formation of resonance rings, such as (P-R and solar wind) drag forces, an elliptical planetary orbit, and gravitational perturbation by an exterior planet (1, 7, 8). Furthermore, understanding of circumstellar dust rings is important in the context of exoplanetary systems (13). Not only are they an important consideration in proposed space-based interferometric imaging of exoplanets (14), large scale rings have been

imaged directly, as in the case of Fomalhaut (15). Here we describe a search for a ring at the orbit of Venus, based on photometry from an exterior viewpoint.

The STEREO mission (16), launched in October 2006, uses two nearly identical spacecraft, A and B, to provide synoptic observations of the Sun and the heliosphere interior to 1 AU. Each spacecraft carries a Heliospheric Imager instrument (17), HI-2, both of which continuously monitor the inner zodiacal cloud. These HI-2A and HI-2B instruments have a field-of-view of about 70° centred on ecliptic latitude $\beta \approx 0^\circ$ at helioecliptic longitude $|\lambda'| = 53.7^\circ$. In searching for a dust ring at the orbit of Venus, the lines-of-sight that are of interest are close to the ecliptic plane and have $40^\circ < |\lambda'| < 50^\circ$ (depending on the location of the spacecraft) (Fig. 1).

In normal science operations, the HI-2 instrument generates a 1024×1024 pixel image with ≈ 4 arcmin resolution every two hours. Further processing, including positional calibration (18), results in the Level-1 data used here. The instrument is sensitive to wavelengths of 400–1000 nm, and the dominant diffuse source in HI-2 images is solar radiation scattered by dust grains (with radii 10–100 μm (19)) in the zodiacal cloud. The typical surface brightness at $(\lambda' \approx 45^\circ, \beta \approx 0^\circ)$ is $\approx 8 \text{ DN s}^{-1} \text{ pixel}^{-1}$ (DN is data number, 1 DN $\cong 15$ photoelectrons is the default unit used by the instrument team (17)). The HI-2 instrument was designed (17) to monitor coronal mass ejections having a surface brightness of about 1% of that of the zodiacal light. By combining ~ 100 HI-2 Level-1 images, photometry on the zodiacal cloud to an accuracy of order 0.1% can be extracted. A major limitation is the presence of systematic errors that compromise this photometry. These arise from various sources: saturation stripes, ghosting caused by bright objects and the presence of the galactic plane within 30° of the region of interest. To avoid contamination, data containing these features were not used in our analysis.

Photometry of HI-2 data involved combining Level-1 images from 10 consecutive days (i.e. up to 120 images, with an integrated exposure time of ≈ 8 days). Surface brightnesses were determined over a grid with extent $|\beta| < 8.5^\circ$, and $35.0^\circ < \lambda' < 60.0^\circ$ (HI-2A) or $-60.0^\circ < \lambda' < -35.0^\circ$ (HI-2B), with cell size of 0.5° in λ' and 1.0° in β . For each cell the cumulative probability distribution of surface brightness was determined using the image pixels within that cell (typically $\approx 14,000$ values). The surface brightness of each cell was estimated as that corresponding to a probability of 0.45 (a value slightly lower than the median is expected due to the presence of point sources). This grid was treated as a series of independent scans at constant β , which were fitted to a power law, $k/|\lambda'|^n$, (20). Each scan was de-trended using a box-car filter of width 6.5° (i.e. $13 \times 0.5^\circ$ cells), followed by subtraction of the result of applying the filter to the best-fitting power-law for that scan. The resultant scans are used in two ways: as a map of extent $38.0^\circ \leq \lambda' \leq 57.0^\circ$ and $|\beta| \leq 8.5^\circ$, and as a mean scan along the ecliptic plane (covering $38.0^\circ \leq \lambda' \leq 57.0^\circ$) by averaging over $|\beta| \leq 4.5^\circ$.

An example map from a 10 day observation period of HI-2B data starting on 2008-Jun-07 00:00 UTC (all data sets are referred to by their starting date), shows a bright feature coincident with the tangent to the orbit of Venus (Fig. 2A). This is as expected for a dust ring along a line of sight where the dust column density is maximised (see Figure 1, noting that the position of the tangent point with respect to Venus is given by the azimuthal angle θ). Given the sensitivity of these maps to systematic errors, this is, in itself, insufficient to demonstrate beyond doubt the existence of such a ring. However, when the same de-trending method is applied to a region $(-67.0^\circ \leq \lambda' \leq -48.0^\circ)$ which does not contain the orbit of Venus, no such bright feature is detected (Fig. S1).

Furthermore, this data set is just one from a 100-day interval (starting 2008-Apr-18) from which 10 consecutive data sets ('b1' to 'b10' in Figure 1) could be analysed. In the mean scans of this sequence (Fig. 2B) the helioecliptic longitude of the feature decreases with time. Because of the spacecraft orbit, the heliocentric distance, r , of STEREO-B varied from 1.02 AU to 1.08 AU over this interval. The view of a physical feature would be expected to change with viewing position, with $|\lambda'|$ decreasing as r increases. The position of the feature was determined (to an accuracy of $\approx 0.25^\circ$) by reference to the point at which the surface brightness is mid-way between the peak and minimum value on the sunward side. Figure 2C shows these positions against r : the behaviour is as expected for a physical ring located close to the orbit of Venus. Finally, there are observations from STEREO-A which view the same tangent point ($\theta=170^\circ$) as the 2008-Jul-17 data. Again, an extended feature is observed close to the orbit of Venus (Fig. S2), further supporting the view that it arises from a physical structure at this location.

In the sequence of mean scans (Fig. 2B), θ changes by $\approx 60^\circ$, hence the feature appears to be an arc occupying a significant fraction of the orbit. In conjunction with further HI-2A data which also show a bright feature near the orbit of Venus (Fig. 3A), but which are $\approx 120^\circ$ away in θ from the HI-2B data (Fig. 1), these data are indicative of a ring (or a series of arcs) which is associated with the orbit of Venus.

The mean scans in Figure 2B allow some inferences to be made about the underlying dust density distribution. The bright feature is asymmetric, with a steeper decline on the sunward side than its other side. This rules out models in which the variation of dust density with r is symmetric around some fixed radius (as in the Gaussian model (21) of the Earth's ring) which would exhibit a peak with the shallower decline on its sunward side.

The majority of the mean scans (Fig. 2B) show evidence of a double peak structure (e.g. 2008-May-08) but there are mean scans from HI-2A data (Fig. 3A) that more clearly reveal the existence of two components to the peak profile. The data from 2009-Jun-09 display a strong sharp peak slightly interior to the orbit of Venus, but with a shallow decline exterior to the orbit. By 2009-Jun-29 the sharp peak has reduced in intensity, while the gradual decline has changed into a second peak. By 2009-Jul-19 there are two very distinct peaks in the mean scan profile. An earlier observation, 2008-Nov-12, shows that the interior peak can be weak, while the exterior peak is relatively strong. There appear, therefore, to be two distinct components to the ring, one just inside and one exterior to the orbit of Venus. Furthermore, the absolute and relative intensities of these two components show considerable variation with θ .

To characterise this observed behaviour, we adopted a simple parametric model to describe the dust density distribution (22). The model is defined in terms of coordinates (r, z, θ) , in which z is the vertical distance from the plane of the ring. The vertical behaviour is modelled as an exponential distribution with scale height S_z (21). The radial dependence is one in which the density changes in two sharp steps (at r_0 and r_1), so the dust density in the ring is $n_q(r) e^{-|z|/S_z}$, where

$$n_q(r) = \begin{cases} 0, & r < r_0 \\ n_{0,q}, & r_0 < r < r_1 \\ n_{1,q}, & r_1 < r \end{cases} \quad (1)$$

A limitation of this model is that the ring density should drop to zero as r increases beyond r_1 . Such a decline cannot be discerned in the maps because of the spatial filtering used. Accepting this limitation, this two-step model was, however, adopted, because it provides an indication of the sharp density changes that appear to be present.

The ring is assumed to be co-planar with the orbit of Venus, and a phase function for optical scattering (23) is adopted. In fitting this model to the maps, the variable parameters were $n_{0,q}$, $n_{1,q}$, r_0 , and r_1 (Table S1). The scale-height was fixed at the weighted mean (of the HI-2A observations) value of $S_z = 0.055$ AU, while noting that genuine variation in S_z with θ cannot be ruled out.

The two-step model provides an adequate description of the data as shown (Fig. 3A) in the data, model and residual (c.f. the ‘no signal’ map of Fig. S1) maps. There are some discrepancies – most notably that the outer step in the model has a sharper peak than is observed – but overall, the model reproduces the range of observed behaviour by variation of a small number of parameters.

Overall, the ring densities are up to $\approx 10\%$ of the density $n_{\text{fan,V}}$ of the smooth cloud (at its symmetry plane) (24). The difference in profiles between 2009-Jun-09 and 2009-Jul-19 can be explained in the two-step model by the variation of the relative difference between the first and second density steps. The profile with a very sharp interior peak (2009-Jun-09) has $n_{0,q} \gg 0.8n_{1,q}$. As the sequence of observations progresses, $n_{0,q}/n_{1,q}$ decreases to ≈ 0.57 , resulting in a double peak profile by 2009-Jul-19. The data from 2008-Nov-12, in which the inner component is weak, has $n_{0,q} \gg 0.4n_{1,q}$. Furthermore, the absolute densities show variation between this observation and the 2009 June/July observations: $n_{1,q} = 0.074n_{\text{fan,V}}$ for the former, while $n_{1,q} \gg 0.10n_{\text{fan,V}}$ for the latter. This is in qualitative agreement with the prediction (1) that the greater drag experienced by dust at the orbit of Venus, and the higher orbital speeds, should result in a ring that is less pronounced than the Earth ring (which has an overdensity of about 0.16 (21)). Also, the data of 2009 June/July represent small (negative) values of θ (-38° to -59°) (25), and the relatively high values of $n_{0,q}$ and $n_{1,q}$ may reflect a density enhancement similar to the so-called ‘trailing blob’ observed in the Earth’s ring (21, 26).

The radii r_0 and r_1 are well constrained and do not exhibit much variation between different data sets. It is notable that r_0 is not only interior to the semi-major axis of the orbit of Venus (0.7233 AU), it is also interior to the perihelion distance of Venus (0.7184 AU). Likewise, the location of the second step, r_1 , is exterior to the aphelion distance of Venus (0.7282 AU). Numerical simulations (14) of resonance rings in exozodiacal clouds predict a sharp change in ring surface density interior to the planetary orbit. In particular, where the ring density contrast exceeds 30% (which admittedly is not the case for the Venus ring), the inner edge is at ≈ 0.83 of the semi-major axis of the planetary orbit (14). Applied to Venus, this implies $r_0 \gg 0.60$ – smaller than observed here. It is also noted that a sharp increase in surface density at a radius exterior to the planetary orbit is apparent in some ring simulations (see catalog (27) linked to (14)).

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The HI-2 level-1 science data used in this study are available from <http://www.ukssdc.ac.uk/solar/stereo/data.html>

Fig. 1. The viewing geometry (from ecliptic north) of a circumsolar dust ring at Venus from STEREO-B. Planet and STEREO spacecraft (A, B) positions are for 2008-Jun-12. A ring at the orbit of Venus (thick gray band) is viewed tangentially from B along a line-of-sight passing through T. The range of helioecliptic longitude λ' mapped is indicated (pale gray). Crosses indicate the locations of T in the observations presented here. The start dates of the STEREO-A data sets are: (a1) 2009-Jun-09, (a2) 2009-Jun-29, (a3) 2009-Jul-19, (a4) 2008-Nov-12. There are ten consecutive sets of STEREO-B data: (b1) 2008-Apr-18 to (b10) 2008-Jul-17.

Fig. 2. A bright feature and its change of position with varying heliocentric distance of the STEREO-B spacecraft. (A) The surface brightness map (lower panel) and mean scan (upper panel) of a 10-day integration of HI-2B data starting on 2009-Jun-7 00:00 UTC. The orbit of Venus as viewed from STEREO-B at the start and end of the integration time is shown by black dots. Surface brightness is expressed in $\text{DN s}^{-1} \text{ pixel}^{-1}$ (pixels are those of the CCD of the HI-2

instrument). **(B)** Surface brightness mean scans for a sequence of ten 10-day periods ('b1' to 'b10' in Figure 1) starting on 2008-Apr-18 00:00 UTC. **(C)** The helioecliptic longitude of the mid-rise point on the sunward side of the peaks in Figure 2B against the heliocentric distance of STEREO-B. The gray curves show the expected behaviour if the feature is associated with a physical ring at the indicated radii.

Fig. 3. Surface brightness mean scans and maps, and model radial density profiles for HI-2A data sets starting at 00:00 UTC on 2009-Jun-09, 2009-Jun-29, 2009-Jul-19 and 2008-Nov-12. **(A)** From the top panel downwards: top – mean scans (blue), with best-fitting models (red). Second panel – maps from the data. Third panel – maps of the best-fitting models. Lowest panel – residual (data minus model) maps. Units are as in Figure 2A. **(B)** The fitted radial density profiles for the 2-step density model shown in Figure 3A. The profile is plotted against the helioecliptic longitude of the tangent point of a ring with heliocentric radius (r). Density is expressed in terms of $n_{\text{fan},V}$ (see main text).

Supplementary Materials:

Supplementary Methods

Additional author notes

Figures S1, S2

Table S1