

A Unique View through the Earth's Resonant Ring

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Abstract. With the advent of infrared telescopes in space, our knowledge of the ubiquitous cloud of dust in the solar system, the *zodiacal cloud*, has increased dramatically. Analysis of IRAS and COBE data has shown that thermal emission from the zodiacal cloud contains structure above the smooth background. This has led to the development of modelling techniques that, by linking the observed structure with the origin and subsequent dynamical evolution of the particles in the cloud, have managed not only to explain the observations, but also to gain an insight into the physics of the cloud. One of these structures is the Earth's resonant ring, a toroidal ring of dust located between $0.8AU$ and $1.3AU$ from the Sun that corotates with the Earth (Dermott et al. 94). We explain how the modelling techniques were used to build up a physical model of the ring and point out its prominent features (figs 1 & 2). We also show how SIRTf's unique orbit, by leaving the confines of the Earth, affords us an unrivalled opportunity to determine the spatial structure of the ring (figs 1b & 3) and discuss the broader implications of SIRTf observations on our knowledge of zodiacal cloud systems.

1. Modelling the Earth's Resonant Ring

While the theoretical possibility of resonant rings has been known for some time (e.g. Gold 75), the first proof of their existence came with the discovery of the T/L asymmetry in the IRAS data — it was noticed that there was a consistent increase in flux from the trailing over the leading direction by a factor of 3-4% irrespective of the longitude of the Earth. This implied that the Earth has some feature associated with it and subsequent modelling showed how the observations are consistent with the existence of an asymmetric resonant ring corotating with the Earth (Dermott et al. 94).

The Earth's resonant ring is formed in the following way: The action of Poynting-Robertson drag (P-R drag) on dust particles in the zodiacal cloud causes them to spiral in towards the Sun. As they pass the Earth, gravitational perturbations to their orbits cause a fraction of the particles to become trapped

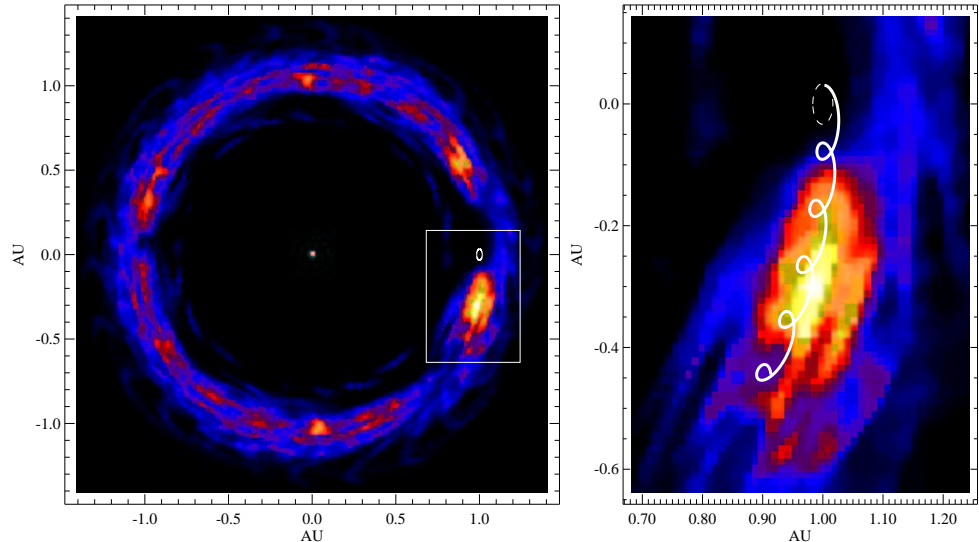


Figure 1. a. The Earth's resonant ring viewed face-on in a frame centred on the Sun and co-rotating with the Earth's mean motion. The Earth's orbit in this frame is almost stationary and is shown as the small ellipse $1AU$ to the right of the Sun. The trailing cloud is the bright part of the ring seen just below the Earth. This is a simulated $25\mu\text{m}$ waveband observation of a model of spherical $12\mu\text{m}$ diameter asteroidal particles of astronomical silicate. b. Close-up of the ring (of the area indicated by the box in fig. 1a) showing SIRTIF's orbit through the trailing cloud. The orbit is shown for a 5.2 year period where the beginning of each cusp marks SIRTIF's location at yearly intervals.

in exterior mean-motion resonances with the Earth¹. Trapped dust remains at this radial location until released from the resonance and this bottleneck causes a local enhancement in the number density of dust. The resultant ring structure, shown in fig. 1 as a face-on view of the solar system, is stationary when viewed in a frame corotating with the Earth's mean motion.

Resonant rings are very complicated systems to model as their exact structure depends on unknown factors, such as the distribution of particle sizes and orbital elements in the background cloud. The model of the Earth's resonant ring shown in fig. 1 is for spherical $12\mu\text{m}$ diameter asteroidal particles of astronomical silicate, the type of particle that is expected to dominate the $25\mu\text{m}$ waveband observation (the waveband in which the T/L asymmetry is most pronounced). By specifying the source and size of particles in each model, we can analyse their complete dynamical evolution from source to sink in order to ascer-

¹In the resonance the particle orbits the Sun p times for every $p + q$ Earth orbits, where p, q are integers. The resonance has a nominal radial location at $a = \left(\frac{\sqrt{1-\beta}(p+q)}{p} \right)^{2/3} a_{\oplus}$.

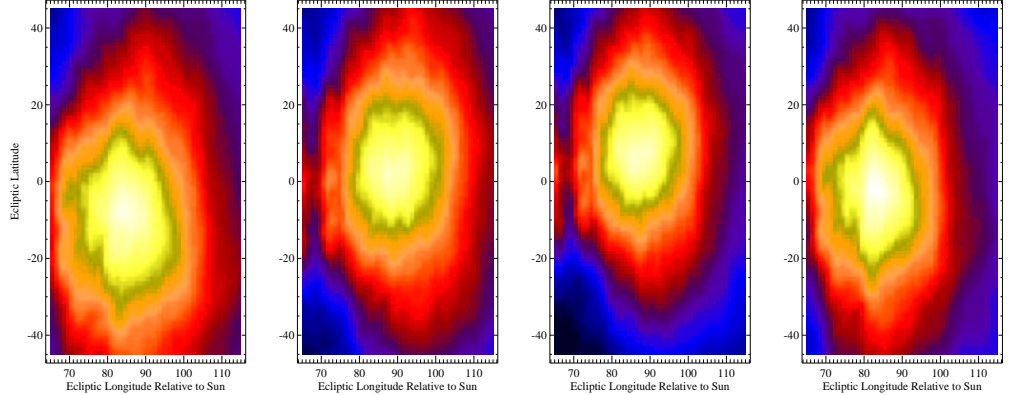


Figure 2. Images of the trailing cloud of the model of the Earth’s resonant ring shown in fig 1 seen from the Earth at longitudes of Earth, $\lambda_{\oplus} = 0^{\circ}, 90^{\circ}, 180^{\circ}, 270^{\circ}$. The plane of symmetry of this model is described by $i_f = 3^{\circ}$, $\Omega_f = 50^{\circ}$, causing the latitudinal oscillation of the trailing cloud.

tain their probability of capture into the different resonances and to understand their subsequent dynamical evolution once caught in resonance. In this way we can establish the distribution of orbital elements of these trapped particles which is then converted to the 3D distribution of surface area of dust in the model (i.e. before and after the particles are in the resonance they are considered to be part of the background cloud). A suite of models of particles from different sources and of different sizes can be made, each of which has a slightly different asymmetric and out-of-plane structure.

The asymmetric structure shown in fig. 1 arises because of the action of P-R drag on the geometry of the resonances. In particular this leads to the formation of the *trailing cloud*, a cloud with a peak number density $\approx 10\%$ above the background cloud that trails $\approx 0.2AU$ behind the Earth, and a smaller *leading cloud* $\approx 0.6AU$ in front of the Earth. This asymmetry is apparent to varying degrees in all of the models (for example models of larger particles exhibit less of an asymmetry) and is the cause of the T/L asymmetry.

The out-of-plane structure of the ring is best illustrated using the simulated geocentric observations shown in fig. 2. This shows how the shape and location of the trailing cloud might appear in the COBE observations at different times of the year, and can be explained by considering the inclination of the ring particles. The probability of capture into a particular resonance, P , depends on the particle’s drag rate (larger particles move slower and so have high P) and eccentricity on encounter with the resonance (highly eccentric particles have low P). It is however independent of the particle’s inclination, which is also not affected by the subsequent dynamical evolution in the resonance.

This means that, just like the Dust Bands (see Grogan & Dermott 99), particles in the ring will precess about a plane of symmetry² which is not necessarily the ecliptic plane. In fact numerical simulations predict that for the particles in the model shown in fig. 1, this plane is described by $i_f = 3^\circ$, $\Omega_f = 50^\circ$. When viewed from the Earth this imposed plane of symmetry means that the trailing cloud will oscillate yearly above and below the ecliptic (the oscillation is $\pm 7^\circ$ in fig. 2). Different models will have different planes, and hence the amplitude and phase of their oscillations will differ.

The actual out-of-plane structure, and hence the observed shape of the trailing cloud, will depend on the origin of the particles in the background cloud. Because cometary particles have a high eccentricity, they are unlikely to be caught in resonances with the Earth unless they have been processed through Jovian resonances that reduce their eccentricity. They will however retain their high inclination and so the resulting out-of-plane structure of the trailing cloud will be broader than the asteroidal structure shown in fig. 2.

2. The Space Infrared Telescope Facility (SIRTF)

Essentially our models of resonant trapping and our knowledge about its associated 3D structure are based on theory and have yet to be proven by hard observational facts (although the existence of the ring has been confirmed in the COBE data, Reach et al. 95). COBE observations will certainly give us a lot of information on the structure of the ring in the coming years, however its geocentric viewpoint means that it only sees one aspect of the ring, limiting the conclusions that we can draw about the asymmetric structure of the ring. SIRTF overcomes this obstacle by its heliocentric orbit at $a = 1.01AU$ which means that it drifts slowly away from the Earth ending up $\approx 0.6AU$ from the Earth after 5 years. Fig. 1b shows how SIRTF's orbit carries it directly through the location of peak number density of the ring, the trailing cloud. The small increase in dust flux from the trailing cloud poses no physical problem to SIRTF, but coupled with the advances in infrared detector technology that have allowed an increase in resolution and sensitivity offered by the instruments carried on SIRTF, observations of the flux variation will allow us to probe the 3D structure of the ring in a way that is unrivalled by the geocentric view of IRAS and COBE.

To give an idea of how much the structure of the ring as observed by SIRTF will vary throughout its mission, and how this can be used to get the best possible insight into the physics of the zodiacal cloud, consider fig. 3. Here we show the variation of the all-sky view of the ring (of the model shown in fig. 1) as viewed from SIRTF at yearly intervals after its launch. We see how the *trailing cloud*, initially seen in the trailing direction, grows in size until SIRTF passes through the middle of the cloud between years 3 and 4, after which the *trailing cloud* appears in the leading direction just to the left of the *leading cloud*, whose size and location do not change much throughout the mission. As SIRTF approaches the trailing cloud, the cloud will appear to oscillate above and below

²The action of the secular gravitational perturbations of the planets imposes a plane of symmetry (or *forced inclination*) on all particles in the cloud that varies with radial distance from the Sun and also depends on the particle's dynamical history. See Dermott et al. 92 for more details.

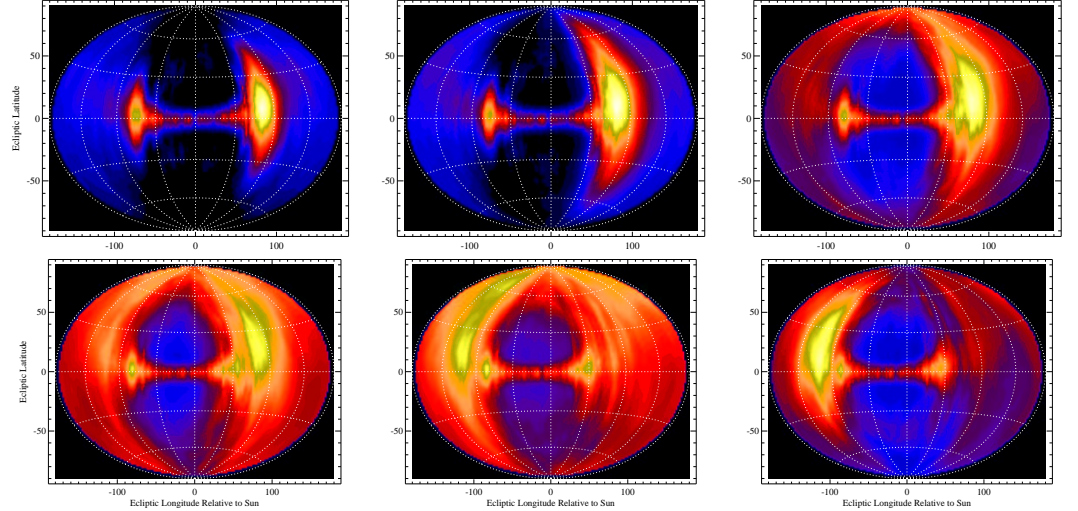


Figure 3. All-sky view of the model of the Earth’s resonant ring shown in fig. 1 as seen from SIRTf at launch and yearly intervals. The view is shown in aïtoff projection with the Sun at the centre, where the satellite’s trailing and leading directions are to the right and left of the Sun respectively, at $\lambda - \lambda_{\odot} = \pm 90^{\circ}$.

the ecliptic, just as in the COBE observations (fig. 2), but the amplitude of the oscillations will increase as SIRTf approaches the cloud (this oscillation is not seen in fig. 3 as it is a yearly oscillation). As the trailing cloud becomes extended and spread out over the whole sky this leads to an increase in flux from the ring in all directions and thus in the total flux received. The total flux from this model (whose number density has been normalised by the T/L asymmetry of the IRAS observations) increases from 3.0MJy at launch, to 11.2MJy at year 2 and 14.8MJy at year 4, decreasing thereafter. This even spread of flux over the sky will make it very difficult to distinguish flux from the ring from flux from the background cloud and a good model for the background flux is needed.

One of the most dramatic changes in flux occurs at the poles, increasing from ≈ 0 MJy/Sr to ≈ 2 MJy/Sr. In fact the polar flux observation is a good measure of the flux from the ring as it is uncontaminated by flux external to the solar system and the flux from the background cloud can easily be subtracted as its variation with longitude and heliocentric distance has been well established by the COBE observations.

Because SIRTf travels through the trailing cloud, whose location and structure vary significantly from model to model, observations of different models will be significantly different. For simplicity we have shown only one model for the ring here, but the modelling of actual observations, that sample particles of a range of sizes, composition and origin, will require the superposition of all of the models. One method to partially isolate observations of individual models is to

compare observations in different wavebands as these sample a different range of particle sizes.

It is this sensitivity of SIRTf's observations to the flux from particles of different sizes and origins that will allow us to determine the combination of models necessary to explain the observations. This not only characterises the structure of the ring, but also gives us vital information about the sources of the particles in the background cloud and their subsequent collisional evolution. The modelling process also helps to refine our understanding of resonant trapping phenomena, which has wide-ranging implications for the other resonant structures in the solar system — the putative resonant rings around the other planets such as Mars and Venus, and the hypothetical cool resonant ring of Kuiper Belt particles around Neptune — and beyond.

3. CONCLUSIONS

We have shown how IR observations have given us an insight into our zodiacal cloud, and how SIRTf will give us a unique opportunity to build on our present knowledge, not only in our understanding of the Earth's resonant ring and resonant trapping phenomena, but also in our understanding of the whole zodiacal cloud system. This is particularly important as an understanding of the physical processes relevant in our own system is the starting point for understanding exozodiacal cloud systems. Technical advances in IR astronomy mean that in the future we can expect to see many more exozodiacal cloud systems (e.g. Holland et al. 98) whose structure will need explanation. The successful application of our modelling technique to the disk of dust around HR4796A (Wyatt et al. 98) shows how portable modelling techniques such as the ones described in this paper are, and how they can be used not only to explain observations of circumstellar disks, but also to give us information about the physical conditions in the disks, possibly leading to the detection of modest-sized planets by their signature on the cloud of dust in which they are embedded. In this respect missions like SIRTf are instrumental to our understanding of the origin and evolution of our own and other planetary systems.

References

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