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The Vega Particulate Shell: Comets or Asteroids?

Abstract. *The Infrared Astronomical Satellite (IRAS) science team has discovered a shell of particulate material around the star Vega. At the mean distance and temperature of the shell, the expected condensation products from a protostellar nebula would be dominated by frozen volatiles, in particular water ice. It is not possible to discriminate between dirty ice and silicate materials in the Vega shell on the basis of the IRAS data. The Vega shell is probably a ring of cometary bodies with an estimated minimum mass of 15 earth masses, analogous to one that has been hypothesized for the solar system. A possible hot inner shell around Vega may be an asteroid-like belt of material a few astronomical units from the star.*

The Infrared Astronomical Satellite (IRAS) science team (*1*) has reported the discovery of a shell of particulate material around the star Vega, α Lyr. The shell has an apparent diameter of 20″, corresponding to a distance from Vega of 85 AU, and its infrared spectrum can be fitted by a blackbody curve with a temperature of 85 K. The observations have been interpreted by the IRAS team as indicating a shell of particulate material with particle diameters on the order of 0.12 cm or more and with a possible mass between 1.2×10^{-2} and 300 earth masses. The existence of the Vega shell has been confirmed by observations at 47 and 95 μm with the Kuiper Airborne Observatory (*2*). Similar shells of material have also been found around the star Fomalhaut, α PsA, and two other stars (*3*).

In our own solar system a shell with a temperature of 85 K would correspond to a location about 10 AU from the sun, roughly the semimajor axis of Saturn's orbit. The small bodies that condensed from the primordial solar nebula at that distance are predominantly water ice, for example, the icy satellites of Saturn. Kuiper has suggested (*4*) that comets, which are primarily water ice, formed among the outer planets prior to being ejected to the sun's Oort cloud.

It is therefore reasonable to ask whether the material around Vega is of cometary or asteroidal origin. If the condensation processes in the proto-Vega nebula were similar to those in the solar nebula, and there is no reason to expect that they were not, then the dominant condensate 85 AU from Vega would be water ice. Ice and dust grains in the proto-Vega nebula would settle toward the nebula midplane, where they would form an accretion disk and then break up and contract into cometesimals through Goldreich-Ward gravitational instabilities (*5*). The Goldreich-Ward theory predicts cometesimals (in our solar system) with typical diameters of 100 to 300 km, although a more recent study (*6*) has shown that accelerated settling of larger dust and ice grains would lead to bodies of more modest size, typically 8 km in diameter, in agreement with estimates for the dimensions of observed cometary nuclei (*7*).

Because of the long orbital period at 85 AU from Vega, 554 years, growth of significantly larger bodies through collisional accretion of the initial cometesimal population would probably not have occurred in the 10^8-year estimated lifetime of Vega. At the expected temperature 85 AU from Vega, water ice bodies would be stable against sublimation over the lifetime of the Vega system. Water ice sublimation rates are fairly negligible at temperatures below about 160 to 170 K (*8*).

Moreover, it is not possible to discriminate between dirty water ice and silicate particles on the basis of the IRAS data. The addition of relatively small amounts of absorbing material to water ice particles sharply reduces their albedo and leads to thermal behavior approaching that of a blackbody as a function of solar distance (*9*). For nonsublimating, fast-rotating particles in orbit about Vega (and if we ignore thermal conduction terms), the mean temperature (in kelvin) is given by

$$T = 767[(1 - A)/r^2]^{1/4} \tag{1}$$

where A is the particles' albedo and r is the distance from Vega (in astronomical units). For a blackbody at 85 AU, Eq. 1 predicts $T = 83.2$ K. For a typical S-type asteroid with $A = 0.15$, T drops to 79.9 K; for a cometary nucleus covered with a bright snow with $A = 0.4$, T is 73.2 K. But, if the snow is dirtied with even small amounts of dark material, A decreases sharply and T increases to close to that for a blackbody. The addition of only 10 percent (by weight) silicate soil to water ice can lower A from 0.48 to 0.14 (*10*); contamination with 10 percent carbon would lower A to 0.10. Typical ratios of dust to ice in comets are estimated to be between 0.5 and 2.0 (*11*).

In addition, if the particles producing the infrared emission from the Vega shell are on the order of several micrometers in size or smaller, then their effective temperature can in fact exceed the blackbody temperature for their distance from Vega. This results from the inefficiency with which micrometer and submicrometer particles radiate energy at thermal wavelengths.

The IRAS science team (*1*) set a lower limit on the diameter of particles in the Vega shell of 0.06 cm, arguing that particles up to 9 μm in diameter would be blown away by radiation pressure and that particles smaller than 0.06 cm would have spiraled into Vega as a result of the Poynting-Robertson effect. However, neither of these arguments need apply if the particles are being continually supplied by sublimation from and collisions between larger bodies orbiting in the shell. Because of the low temperature of the Vega shell, water-ice sublimation would be negligible and a more volatile ice such as methane ice would be required. As the ice sublimated, dust particles and water-ice grains embedded in the ice-dust mix would be freed from the comets and ejected into the Vega dust shell. The presence of significant amounts of methane has been observed in solar system comets (*12*).

For collisional generation of dust we must consider mean collision times in the Vega shell. The IRAS team found an optical thickness, τ, for the shell of 2.5×10^{-5}, assuming a spherical shell 85 AU from Vega. The mean time between collisions for any particle in such a shell is given by (*13*)

$$t = (\Omega\tau)^{-1} \quad (2)$$

where Ω is the orbital frequency. For a 554-year orbital period, $t = 3.5 \times 10^6$ years. But, if the thermal emission is modeled instead as coming from a flattened disk with a radius of 85 AU, the opacity increases to 10^{-4} and the collision time drops to 9×10^5 years. Modeling the material as a ring with a width of 20 AU centered at 85 AU increases the opacity further and drops the mean time between collisions to 4×10^5 years. Only particles less than about 14 μm in diameter will spiral into Vega due to Poynting-Robertson effects on that time scale. Thus collisions between comets in the Vega shell or ring are still probably occurring with sufficient frequency to extend the particle size distribution down to the size range of tens of micrometers.

If the thermal radiation of the shell is coming primarily from particles of this size range, then the mass estimate for the shell given by the IRAS team must be reduced. Following the method used in their paper (*1*) and assuming an asteroidal size distribution, a minimum particle size of 14 μm, and a maximum particle size of 1000 km gives an estimated shell mass of 46 earth masses as compared with the IRAS value of 300 earth masses. If the diameter of the largest cometesimal is only 100 km instead of 1000 km, assuming slow growth of larger bodies, then the total shell mass drops further to about 15 earth masses.

Any estimate of the mass of the Vega shell or ring is highly uncertain because the thermal radiation seen by IRAS comes primarily from the smallest particles (highest surface-to-mass ratio), whereas with the adopted size distribution most of the mass is in the largest particles. We have no knowledge of the Vega particle size distribution or its maximum cutoff. For known solar system values, the slope of the particle size distribution repeatedly changes for different particle size ranges and for asteroidal versus cometary bodies. Thus, the mass estimates given here should be regarded only as first-order, speculative values.

The Vega shell is much closer to its central star than the sun's Oort cloud, estimated to have a radius of about 5×10^4 AU and a population of 2×10^{12} comets (*14*). But several investigators have hypothesized the existence of a massive inner Oort cloud much closer to the planetary region. A comet belt beyond Neptune could serve as a possible source of short-period comets (*15*), might explain the perturbations on the orbit of Neptune (*16*), and could account for some of the cool infrared sky background detected by IRAS at 100 μm (*17*). Some theories of solar system formation propose a massive inner Oort cloud resulting from the condensation of icy cometesimals in a planetary accretion disk beyond the orbit of Neptune, up to several hundred astronomical units from the sun (*18*). An examination of the distribution of observed long-period comet orbits has indicated that they are consistent with a "centrally condensed" distribution of comets in the Oort cloud (*19*). A massive inner comet cloud is also capable of repopulating the outer Oort cloud after a close encounter between the solar system and a giant molecular cloud has stripped away the more distant comets, thus refuting arguments that the Oort cloud could not survive such encounters (*20*).

Even closer to the sun it is likely that a significant fraction of icy planetesimals are still circulating in, or just beyond, the Uranus-Neptune zone. The mean half-life for objects in Uranus- and Neptune-crossing orbits is on the order of 10^9 years, and roughly 1 percent of the original planetesimals in that zone would be expected to have avoided removal from the zone by either dynamical ejection or collision. The possibility that a much larger fraction of Uranus-Neptune planetesimals, ~ 9 percent of the original number, might survive in orbits just beyond Neptune has also been suggested (*21*). The minor planet Chiron, which is in an unstable Saturn-crossing orbit, is probably one of these planetesimals from the Uranus-Neptune zone.

Thus, the material making up the shell around Vega is very likely composed of cometary-like bodies with sizes ranging from asteroidal dimensions (10^2 to 10^3 km in diameter) down to particles tens of micrometers in diameter that are producing most of the thermal radiation observed by IRAS. Using the IRAS data, one is not able to discriminate between a spherical shell and a circular ring of material around Vega at 85 AU. Dynamical interactions between shell particles and accretionary processes would probably have flattened the shell into a ring.

It is improbable that the Vega ring contains planetary-sized bodies. The accretionary times for large bodies at this distance from Vega are too long because of the long orbital period and the short estimated age of the Vega system. This does not preclude the possible existence of planets closer to Vega.

Another feature of the IRAS data for Vega is a possible excess in the 12-μm band, which can be interpreted as an inner shell of hotter material, possibly as warm as 500 K. From Eq. 1 that temperature would correspond to a distance of 2.4 AU for a shell or ring of blackbody emitters or 2.2 AU for typical S-type asteroids. These distances are inner limits for the hot shell, since the 500-K blackbody fitted by the IRAS team is an upper limit. At 12 μm Vega appears as a point source to IRAS, an indication that the hot inner shell, if it is real, is located close to the star. At the distances under discussion, the expected condensates from a protostellar nebula would be silicates and other refractory materials. The mean distance of the sun's asteroid belt is 2.8 AU.

It is not immediately apparent why the Vega shell is limited in extent to 85 AU. This may reflect the detection limits of IRAS, or it may represent a real physical cutoff. In the latter case further analysis may yield some insight into physical and dynamical processes in protostellar accretion disks. The lack of warmer structures interior to the 85-K, 85-AU shell (except for that inferred from the possible 12-μm excess) may be indicative of the sweeping up of fine material by planets orbiting around Vega.

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Time-Domain Reflectometry: Simultaneous Measurement of Soil Water Content and Electrical Conductivity with a Single Probe

Abstract. *Two parallel metallic rods were used as a wave guide to measure the dielectric constant and electrical conductivity of soils having different electrical conductivities but the same water content. Measurements showed that the two parameters were sufficiently independent to permit simultaneous determinations of water content and bulk electrical conductivity.*

Conventional nondestructive methods for measuring the water content of soil are based on the use of neutron probes and less frequently on the attenuation of gamma rays (*1*). Soil water conductivity is tediously determined by sampling the soil and measuring the electrical conductivity of saturated extracts (*2*). Time-domain reflectometry (TDR) is a relatively new method for measuring the volumetric water content of a porous medium. It was first developed by Fellner-Feldegg (*3*) in an effort to obtain in one measurement the frequency dependence of the dielectric constant of liquids. In addition, molecular relaxation times and electrical conductivities could be measured. Topp *et al.* (*4, 5*) showed the general applicability of the method for measuring the volumetric water content of soils and other porous materials. They found that there is a unique relation between the volumetric water content and the dielectric constant for many different soils. One obtains the dielectric constant of the medium by measuring the transit time of an electromagnetic pulse launched along a pair of metallic, parallel rods of known length embedded in the porous medium (Fig. 1). In a saline soil, however, the electromagnetic pulse is attenuated (*4*). The purpose of this study was to determine if the attenuation of the launched signal in a conductive medium could be used to measure soil salinity. If the measurements of transit time and attenuation are sufficiently independent, then the conductivity and dielectric constant can be determined simultaneously.

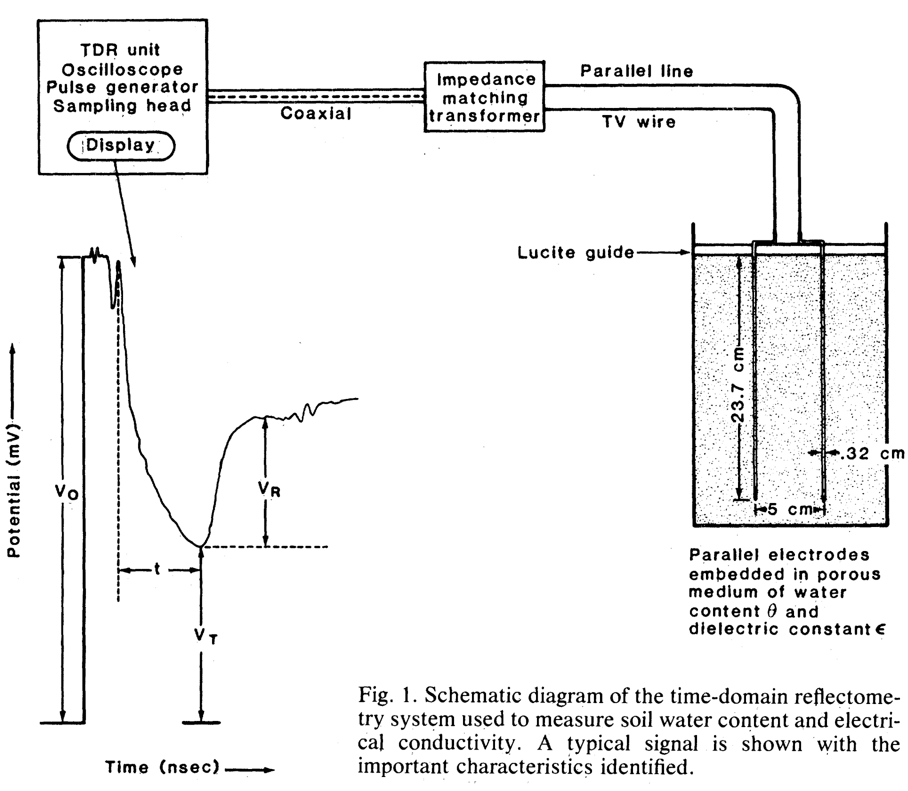

Fig. 1. Schematic diagram of the time-domain reflectometry system used to measure soil water content and electrical conductivity. A typical signal is shown with the important characteristics identified.

At the end of the wave guide, the launched electromagnetic pulse is reflected back to its source. Therefore, the pathlength is twice the length of the wave guide, L (in meters). The measured transit time, t (in seconds), gives the propagation velocity of the pulse (in meters per second):

$$v = \frac{2L}{t} \tag{1}$$

If dispersion is negligible, then v can be given simply in terms of the relative dielectric constant of the medium, ϵ, and the velocity of light in free space, c (3×10^8 m/sec),

$$v = \frac{c}{\epsilon^{1/2}} \tag{2}$$

Therefore, the relative dielectric constant is given by

$$\epsilon = \left(\frac{ct}{2L}\right)^2 \tag{3}$$

Figure 1 shows a schematic of a TDR system used to obtain t; V_0 represents the output of the pulse generator, V_T is the magnitude of the voltage pulse that enters the parallel-rod wave guide, and V_R designates the magnitude of the reflected wave when it has returned to the wave-guide input (*3*). In order to be able to distinguish t, V_R must be greater than zero. In a nonconducting medium, V_R will be equal to V_T and t is easily measured. However, when the medium is conductive, as in a saline soil, the amplitude of V_T will be attenuated in proportion to the conductivity. The attenuation of V_T can be used to measure the electrical conductivity of the medium and therefore the salt content.

According to electromagnetic field theory, the amplitude of a signal traveling a distance $2L$ in an electrically conductive medium with an attenuation coefficient α is diminished exponentially according to

$$V_R = V_T \exp(-2\alpha L) \tag{4}$$

where the attentuation coefficient, α, is approximated by

$$\alpha = \frac{\sigma}{2}\left(\frac{\mu\mu_0}{\epsilon\epsilon_0}\right)^{1/2} \tag{5}$$