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ON THE NATURE OF THE MATERIAL SURROUNDING VEGA

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ABSTRACT

Observations of Vega at 193 μm indicate that the far-infrared emission from the circumstellar material discovered by *IRAS* (Aumann *et al.* 1984) may decline more rapidly than a Planck spectrum at wavelengths greater than 100 μm. This suggests that the emitting particles may be smaller than the millimeter-sized objects proposed by Aumann *et al.* (1984). Small grains would be driven from the stellar system by radiation pressure, or their orbits would decay as a result of Poynting-Robertson drag. In order to maintain a state of dynamic equilibrium, a continuous supply of new particles would be required. We hypothesize that the small grains are ejected by sublimation of volatile material from larger comet-like bodies in a partially coalesced preplanetary disk. A reservoir containing less than a few hundred Earth masses could sustain the source over the lifetime of the star.

Subject headings: stars: circumstellar shells — stars: individual

I. INTRODUCTION

One of the most interesting early results from the *Infrared Astronomical Satellite* (*IRAS*) was the discovery of an unexpectedly large flux from the A0 star Vega at wavelengths of 25, 60, and 100 μm (Aumann *et al.* 1984). The far-infrared emission appears to come from a source with an angular radius of ~ 10″, corresponding to a physical radius of 80 AU. Between 25 and 100 μm, the excess above the spectrum expected from the stellar photosphere fits a blackbody spectral distribution with a temperature of ~85 K. This led to the suggestion that the flux arises from relatively large (millimeter-sized) particles orbiting the star. Smaller particles would either be blown away by radiation pressure or pulled into the star by Poynting-Robertson drag during the time elapsed since Vega condensed from its prenatal cloud (probably 1–2 × 10^8 yr). Larger bodies would require an excessively large total mass.

Measurements at wavelengths longer than 100 μm can provide valuable additional information. Smaller particles would have emissivities which fall more rapidly than a Planck spectrum at wavelengths large compared with the grain size. If the ranges of the particle sizes and temperatures were not too large, the integrated spectrum might mimic blackbody emission between 25 and 100 μm yet decline more rapidly at longer wavelengths. Observing flux densities lying above a blackbody spectrum might reveal the presence of material cooler than 85 K.

We report here measurements at a wavelength of 193 μm which suggest that the long-wavelength spectrum is steeper than a Planck spectrum. We also examine the hypothesis that the emission arises from small particles.

II. OBSERVATIONS

The observations were made with the University of Chicago "H1" photometer on four separate flights aboard NASA's Kuiper Airborne Observatory during 1983 September. We used an 85″ diameter aperture, a metal-mesh bandpass filter with half-power points at 156 and 285 μm, and a 2′.5 spacing between signal and reference beams. The filter passband was determined from measurements with a Fourier-transform spectrometer. In order to ensure that there were no short-wavelength light leaks when observing Vega, we added extra short-wavelength blocking filters to the system (an extra 0.75 mm of Teflon at 2 K and a black polyethylene/diamond dust scattering filter at the nitrogen-cooled radiation shield augmented the blocking previously provided by 1.5 mm of Teflon, the polyethylene/diamond dust Dewar window, and two reflections from thallium bromide crystals). Broad-band filter measurements with laboratory radiation sources indicate that the contribution of out-of-band flux from Vega to the observed signal should be less than 1%.

The absolute calibration was derived from the thermal model of Mars presented by Wright (1976) and Wright and Odenwald (1980). W3(OH) was used as an intermediate calibration source. We reduced signal ratios to flux densities using the procedure outlined in Loewenstein *et al.* (1977). The effective wavelength of the measurement was 193 μm, assuming a spectral distribution like an 85 K blackbody and 15 μm of precipitable water vapor. The measurements, dates of the observations, and additional data on observing times and water vapor are presented in Table 1.

The mean signal for the four flights was 1.0 ± 0.5 Jy. The median signal was 0.95. The empirical cumulative probability distributions (see Daniel and Wood 1971) for the data sets shown in Figure 1 indicate that the residuals are well described by a normal probability distribution. For a more complete discussion of the calibration, see Hildebrand *et al.* (1984).

III. DISCUSSION

Both our 85″ beam and the *IRAS* beam are much larger than the 20″ source diameter derived from the *IRAS* results, so we will assume in the following discussion that no aperture size corrections are necessary. The 193 μm flux predicted from extrapolation of an 85 K blackbody curve drawn through the *IRAS* points at 25, 60, and 100 μm (Aumann *et al.* 1984) is 2.8 Jy. The *IRAS* data, our 193 μm measurement, and an 85 K blackbody curve fitted through the *IRAS* points are shown in Figure 2. If we assume that the *IRAS* and KAO calibration uncertainties are independent and both equal to ±15%, we might expect the relative uncertainty of the 193 μm observation with respect to the extrapolated *IRAS* flux density to be larger by a factor of $\sqrt{2}$, or ±21%. Quadratically combining this value with the statistical uncertainty of 0.5 Jy in the KAO

TABLE 1

OBSERVATIONS

Date (1983)	H_2O[a] (μm)	ΔH_2O[b] (μm)	t_{int}[c] (s)	τ[d] (s)	Vega/W3(OH)[e]	k[f]
Sep 12/13..........	15.5	−1.5	4224	16	$(3.9 \pm 2.0) \times 10^{-4}$	0.984
Sep 14/15..........	14.5	−2.5	3456	16	$(3.5 \pm 2.2) \times 10^{-4}$	0.976
Sep 19/20..........	18	4.0	816	8	$-(2.6 \pm 3.2) \times 10^{-4}$	1.024
Sep 27/28..........	13.5	1.0	3840	8	$(1.3 \pm 1.5) \times 10^{-4}$	1.001

[a] The amount of precipitable water vapor above the aircraft, measured with the KAO total-power radiometer.

[b] The difference in water vapor between observations of Vega and W3(OH) [Vega − W3(OH)].

[c] The total observation time, in seconds.

[d] The time for a single integration (one-half of the beam-switching period).

[e] The ratio of signals of Vega to W3(OH). Uncertainties are 1 standard deviation of the mean.

[f] Corrections for absorption due to water vapor, based on the measurements in the third column and atmospheric attenuations derived from the model of Traub and Stier 1976.

measurement, we derive a predicted flux density of 2.8 ± 0.8 Jy. For normally distributed data, the probability of observing a value of ≤ 1.0 Jy, when the actual value is 2.8 and the standard deviation of the mean is 0.8, is 0.015. Thus it is highly unlikely that the circumstellar emission from the material around Vega follows a Planck distribution. No single-temperature blackbody distribution can be fitted through the error bars shown in Figure 2. Spectra arising from blackbodies having a range of temperatures fit even more poorly, since any simple curve drawn through the data points will be narrower than a Planck function.

Although it might be possible for millimeter-sized or larger particles to have a surface emissivity which declines rapidly

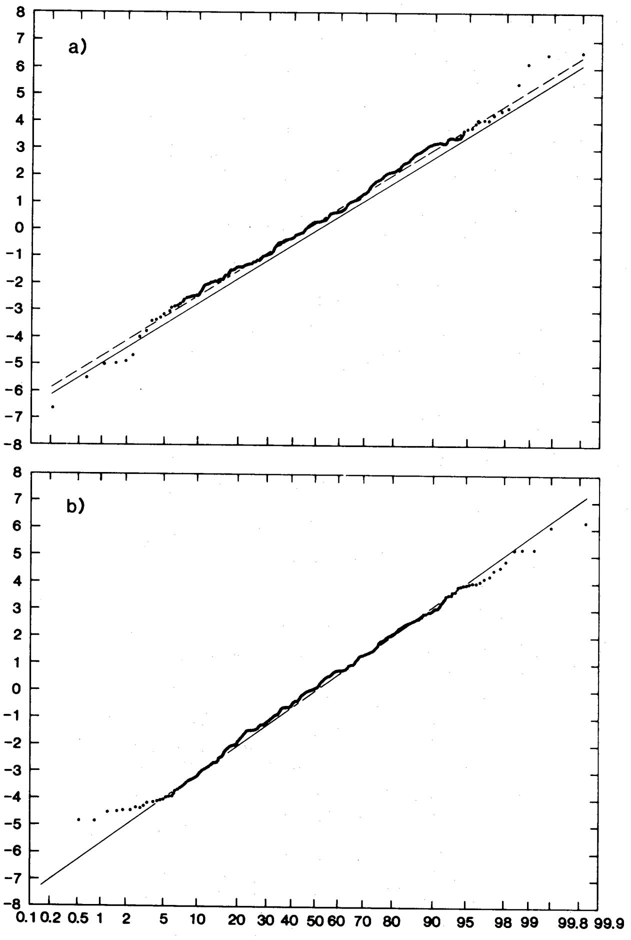

FIG. 1

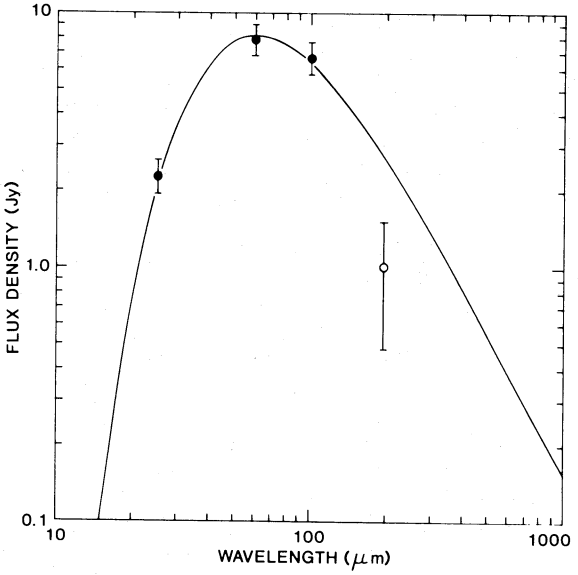

FIG. 2

FIG. 1.—Empirical cumulative probability distributions for the 193 μm observations of Vega. The solid lines are drawn through zero signal (the ordinal displacement of the data at an abscissa of 50% is equal to the median) with slope equal to that predicted from the observed standard deviation of the data. Fig. 1*a* shows all data taken with $\tau = 16$ s, and Fig. 1*b* shows all data taken with $\tau = 8$ s (2τ is equal to the beam-switching period). The dashed line in Fig. 1*a* is parallel to the solid line and passes through the median for the $\tau = 16$ s data. Comparisons with data drawn from normal distributions (see Daniel and Wood 1971) indicate that the Vega data are also normally distributed.

FIG. 2.—Far-infrared continuum spectrum as determined from *IRAS* data (Aumann *et al.* 1984, *solid points*) and the 193 μm measurement (*open circle*) presented in this paper. Error bars shown on the *IRAS* points represent an assumed calibration uncertainty of ±15%. The uncertainty shown for the 193 μm point is the quadratic sum of the observed statistical uncertainty and an assumed calibration uncertainty of ±15%. The curve is an 85 K Planck curve fitted to the *IRAS* data.

between 100 and 200 μm, it seems more productive at this time to consider the hypothesis that the emission arises from grains with radii $a \lesssim \lambda/2\pi$, where $\lambda \sim 193$ μm (i.e., $a \lesssim 31$ μm, although the grains could be somewhat larger if they are composed of material which is particularly absorptive at 30–100 μm). In view of the argument that the stellar radiation field will continually remove such particles from the vicinity of the star on time scales short compared with Vega's lifetime, this would require the existence of some sort of dynamical equilibrium. Larger bodies which are broken up by collisions or stellar heating could provide a source for the small grains.

The *IRAS* data suggest that the radius of the far-infrared source is $\sim$80 AU (corresponding to an angular radius of $\sim 10''$). A body with a flux-integrated absorptivity of ϵ_a (for which the principal contribution to the integral comes in the optical and near-ultraviolet) and a flux-integrated emissivity of ϵ_e (for which the dominant contribution to the integral is in the far-infrared) will reach radiative equilibrium at a temperature T such that

$$\frac{\epsilon_a}{\epsilon_e} = 16\pi\sigma R^2 T^4 L^{-1} ,$$

where σ is the Stefan-Boltzmann constant, R is the distance from the star, and L is the stellar luminosity. For $R = 80$ AU, $L = 58\ L_\odot$, and $T = 85$ K, this would imply $\epsilon_a/\epsilon_e = 1.1$. We conclude that the particles cannot have radii much smaller than $a = \lambda\epsilon_a/2\pi$, where $\lambda \sim 60$ μm (i.e., $a/\epsilon_a \gtrsim 10$ μm). In the following discussion, we will set $\epsilon_a = 1$ and allow an error of a factor of 3 in our estimates of maximum and minimum sizes. That is, we will consider particles with radii lying within the range 3 μm $\lesssim a \lesssim$ 100 μm. In the cases of some dielectrics (in particular, H_2O ice), ϵ_a may, in fact, be significantly smaller than unity (see, e.g., Greenberg 1968). However, we will argue below that the grain parameters and radiation forces scale in such a way that this will have a relatively minor effect on our conclusions. Presumably, better measurements of the spectrum could be combined with detailed computations of emissivities for candidate grain materials to refine our estimates. In the discussion which follows, we will consider only the most general implications of the hypothesis that the emitting particles are small.

We propose, then, that the far-infrared emission comes from grains with radii in the range 3 μm $\lesssim a \lesssim$ 100 μm which are ejected from bodies large enough to be stable against Poynting-Robertson drag over Vega's lifetime of $\sim 10^8$ yr (radii $\gtrsim 10^{-1}$ cm). Such objects could, for example, be part of a partially coalesced preplanetary disk. Note that this hypothesis differs from that of Aumann *et al.* (1984) in that these larger bodies need not directly absorb enough stellar flux to equal the observed infrared luminosity.

The small grains could be released from their parent bodies during collisions, but it seems more likely that they are ejected via sublimation of volatile gases under the influence of direct stellar heating. The total heating flux from Vega at a distance of 80 AU is equal to the flux from the Sun at a distance of $\sim$10 AU. This is approximately the distance at which comets become active in our solar system (Sekanina 1973, 1975). Such activity requires the presence of ices more volatile than H_2O. Sekanina speculates that the grains which form the tails of distant comets may be relatively large ($a \gtrsim 50$ μm) particles composed of complex "snows" such as the clathrate hydrates studied by Delsemme and Wenger (1970).

In order to estimate the rates at which grains emitted from larger parent bodies are lost from the infrared source, we need additional information on their orbits. We will assume that the parent bodies have circular orbits of radius R_0 and that the grains are emitted with velocities small compared with the initial orbital velocity. The orbits of the emitted grains are then given by

$$R = \frac{R_0}{1 - \beta(1 - \cos\theta)} ,$$

where

$$\beta = \frac{3L\epsilon_a}{16\pi c G M \rho a}$$

is just the ratio of the radiation force to the gravitational force (c is the speed of light, and M is the mass of Vega). Particles with $\beta \geq 0.5$ follow unbound orbits. For Vega, this implies that particles with $a\rho/\epsilon_a \leq 0.0035$ g cm^{-2} will escape.

The length of time during which unbound grains can make a significant contribution to the infrared flux should be of the order of the time required to move from the point at which they are separated from their parent body to a radius of $R_m = \sqrt{(2)}R_0$. At that point, the power received from the star (and contributed to the infrared source) will have dropped to half of its value at R_0. This time is

$$t_m = \int_0^{\theta_m} d\theta \frac{R_0}{\sqrt{(GM/R_0)}[1 - \beta(1 - \cos\theta)]^2} ,$$

where

$$\theta_m = \cos^{-1}\left[\frac{1 - \sqrt{(2)}(1 - \beta)}{\sqrt{(2)}\beta}\right] .$$

Grains with $\beta < 0.15$ will always have $R < \sqrt{(2)}R_0$.

For an optically thin source, the spectral mass density of grains of radius a radiating a fraction ηda of the observed infrared flux is

$$M_G = \frac{16\pi\langle R^2\rangle a\rho}{3\epsilon_a}\left(\frac{L_{\rm IR}}{L}\right)\eta .$$

(To obtain the total grain mass for some particular size distribution η, one must integrate over a.) From Aumann *et al.* (1984), $L_{\rm IR}/L \sim 2.5 \times 10^{-5}$ (actually, this is an upper limit, since our data indicate that the flux density falls faster than a Planck curve at $\lambda > 100$ μm). For $\epsilon_a = 1$ and $\langle R^2\rangle^{1/2} = 80$ AU, we find that

$$M_G = 6 \times 10^{26}\left(\frac{a\rho}{\epsilon_a}\right)\eta \text{ g cm}^{-1} .$$

Or, in units equal to the mass of the Earth,

$$M_G = 0.1\left(\frac{a\rho}{\epsilon_a}\right)\eta\ M_\oplus \text{ cm}^{-1} .$$

The mass loss rate of grains of radius a is approximately $M_G/\eta t_m$. For $0.0003 < a\rho/\epsilon_a < 0.0035$ g cm^{-2} and $R_0 = 70$ AU, $M_G/\eta t_m$ lies between 1×10^{-6} and 3×10^{-6} $M_\oplus$ yr^{-1}. Hence, the total mass loss over $\sim 10^8$ yr (if the loss rate were constant) would be at most a few hundred Earth masses ($\sim 10^{-3}$ solar masses).

If a significant fraction of the radiating particles have stable, bound orbits, the total mass required to sustain a dynamical equilibrium may be substantially reduced. The lifetimes of such grains set by the Poynting-Robertson effect are much larger than their transit times between R_0 and $\sqrt{(2)}R_0$. For a particle in a circular orbit, the lifetime against Poynting-Robertson drag is

$$t_{\rm PR} \approx 6 \times 10^8 \left(\frac{R}{80\ \rm AU}\right)^2 \left(\frac{\rho a}{\epsilon_a}\right) \rm yr$$

(Wyatt and Whipple 1950). Since $t_{\rm PR}$ and M_G are both proportional to $\rho a/\epsilon_a$, the mass loss rate is independent of grain parameters and equal to $\sim 2 \times 10^{-10}\ M_\oplus\ \rm yr^{-1}$.

Could the mass reservoir for the infrared source consist of 35–100 μm grains at much larger distances than 80 AU? Since the Poynting-Robertson lifetime varies as R^2, particles now seen at $\sim$80 AU would have had to originate at a distance of 400–800 AU a few hundred million years ago. An origin at smaller distances would require that the grains lie in a disk which is sufficiently thin to have a large optical depth to stellar radiation. This seems unlikely. As seen from Vega, such a disk would be only 10″ wide. A more reasonable width—say, a few degrees (comparable to the relative inclinations of the orbits of the planets in our solar system)—would imply an optical depth $\lesssim$0.003. Since for a given grain radius the product of Poynting-Robertson lifetime and angular cross section (as seen from Vega) is constant, we might expect approximately equal contributions to the far-infrared flux from grains having a very broad range of temperatures—in contradiction to the relatively narrow spectrum implied by the 193 μm data.

The 35–100 μm grains could, of course, come from larger bodies, as suggested previously. In this case, grain ejection at a distance of 60–80 AU would result in elliptical orbits, for which Poynting-Robertson drag is less important than in the case of circular motion. The decay of such orbits may proceed in a complex manner as the particles sublime and/or fragment further because of stellar heating (see, e.g., Burns, Lamy, and Soter 1979). If the bound particles survive only a few orbits, their lifetimes within the infrared source will be a few times t_m. The ratio $M_G/\eta t_m$ increases by only 25% as $\rho a/\epsilon_a$ increases from 0.0035 to 0.01 g cm^{-2}. If the particles are more durable, the corresponding mass loss rates would be lower, but we might also expect to see a somewhat larger contribution to the far-infrared flux from grains at optical radii greater than $\sqrt{(2)}R_0$.

As mentioned earlier, ice grains could have optical absorptivities significantly smaller than unity. In this case, the mass of grains of a given radius required to provide the observed optical cross section would be larger by a factor of $\epsilon_a{}^{-1}$. However, the grain radius needed to explain the observed grain temperatures would decrease. The exact factor will depend on the assumed optical constant for the grain material and on the stellar spectrum. Calculations for pure $\rm H_2O$ ice illuminated by a solar spectrum have been presented by Lamy and Jousselme (1975). At a distance of $\sim$10 AU (where the bolometric heating is approximately equivalent to that at a distance of 80 AU from Vega), their results suggest that a far-infrared spectrum like Vega's could arise from grains with radii of less than 10 μm, or even less than 1 μm (the equilibrium temperature becomes essentially independent of grain radius for grains smaller than the wavelength of peak stellar emission). If we take a somewhat more conservative approach and assume that the grain radii are smaller by only a factor of ϵ_a, we find that both the total mass required and β, the ratio of the radiation force to the gravitational force, would be unchanged. Since a particle's orbit (and thus t_m) depends only on β, the upper limit to the mass flux obtained by assuming all of the grains have $\beta = 0.5$ would be similar to that obtained for the "black" particles discussed previously.

Finally, we note that the mass loss rate may not be constant. If the radial distribution of the mass reservoir is nonuniform, we might expect the infrared flux to vary as the stellar flux increases (the luminosity of an A0 star increases by $\sim$30% during its main-sequence lifetime). The mass supply could also change as a result of coalescence into larger bodies or as a result of perturbations by planets.

The outer planets of the solar system probably formed from the sort of material required for the mass reservoir discussed above. The densities of Uranus and Neptune indicate that their combined mass of $\sim$32 $M_\oplus$ must consist largely of elements heavier than helium. Assuming that the abundances of the elements composing Jupiter and Saturn are approximately solar, the total mass of elements heavier than helium in the outer planets is $\sim$38 $M_\oplus$. Safronov (1972*a*, *b*) has estimated that Uranus and Neptune may have taken longer than 10^9 yr to condense into objects of planetary mass. Hence, the proposed mass reservoir may well be stable against condensation for longer than the lifetime of Vega. Safronov also asserts that in order for Uranus and Neptune to have condensed within the Sun's lifetime, the initial mass of solids in the outer solar system must have been at least 300–350 $M_\oplus$, a value similar to that required to sustain the infrared source around Vega under our assumptions of small grains and a constant mass loss rate.

Anticipated improvements in our photometer should permit better measurements of the far-infrared emission spectrum next year. Also, if the hypothesis outlined above is correct, it may be possible to detect emission from the gas liberated along with the dust grains. Although very distant comets in our solar system do not typically display strong gaseous emission (Roemer 1962; Sekanina 1975), the ratio of ultraviolet to boiometric flux is larger for Vega than for the Sun, and the level of activity could be higher.

IV. CONCLUSIONS

Measurements at 193 μm indicate that the far-infrared spectrum of the circumstellar material around Vega decreases faster than a blackbody at wavelengths longer than 100 μm. This suggests that the emitting particles may be small ($a \lesssim 100$ μm). If so, the material must be continually replenished from larger masses, since small grains will be swept out of the stellar system by radiation pressure and/or depleted by the Poynting-Robertson effect. A partially coalesced planetary disk could provide such a reservoir. The size of the source region is consistent with the radiation densities necessary to eject grains from parent bodies similar to the nuclei of comets, and the mass flux implied by the intensity of the far-infrared emission requires a reservoir of less than a few hundred Earth masses to sustain the source over the lifetime of the star.

Note added in manuscript 1984 March.—After this paper was completed, we were informed by F. C. Gillett that the flux densities reported for Vega (Aumann *et al.* 1984) should be multiplied by factors of 1.00, 1.16, 1.20, and 1.26 at 12 μm, 25 μm, 50 μm, and 100 μm, respectively, in order to agree with the provisional calibration published by Neugebauer *et al.* (1984). This would further increase the discrepancy between the extrapolated *IRAS* data and our 193 μm point.

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