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Vega: smaller dust grains in a larger shell

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Abstract. We have re-analysed the IRAS pointed observations of Vega. We find that the 60 μm emission of Vega is as extended as 35 ± 5 arcsec. This is much larger than the generally accepted 23 arcsec (Aumann et al. 1984). Adopting a distance for Vega of 8.1 pc, the IR emission must be originating from a dust shell with a radius of 140 AU. This implies that a significant fraction of the dust grains is larger than 0.1 μm, but smaller than 10 μm. Thus, to explain the 60 μm emission of Vega the presence of grains larger than 10 μm is not necessary. However, as the smallest grains ($a < 10$ μm) are blown away due to the radiation pressure, and the remaining small grains ($a < 1$ mm) have spiralled into the star due to the Poynting-Robertson effect, a continuous production of small grains must be going on.

Key words: circumstellar matter – stars: individual: Vega – planetary systems – infrared: stars

1. Introduction

One of the highlights of IRAS was the discovery of a large infrared (IR) excess in the spectrum of Vega, α Lyrae (Aumann et al. 1984). This IR excess indicates that Vega, an A0 main sequence star and photometric standard, is surrounded by circumstellar dust. We may be witnessing a late phase of the formation of a planetary disc.

Shortly after the discovery of the IR excess at wavelengths of 12 μm and beyond, just at the end of the IRAS mission, special Pointed Observations (POs) were taken of Vega, in order to spatially resolve the IR excess. Aumann et al. (1984) analysed these spatial observations and found that the 60 μm emission extends over 23 arcsec. At a distance of 8.1 pc (Jenkins 1963) this corresponds to a dust shell with a radius of 80 AU. By fitting a black body spectrum to the flux distribution between 25 and 100 μm, Aumann et al. found the dust temperature to be $T_d = 85$ K. On the basis of the energy balance of this dust shell, Aumann et al. (1984) argued that, to be that cool, so close to the star, the grains should be larger than 10 μm. This is much larger than interstellar particles ($a = 0.01$ μm).

The result of Aumann et al. is supported by the fact that small grains (< 10 μm) would either be blown away from the stellar neighbourhood by radiation pressure, or have spiralled into the central star due to the Poynting-Robertson (PR) effect. The time scale of the PR effect, t_{PR}, is proportional to the size of the grains. Large particles will be less affected by the PR effect than small particles, and will remain longer in the circumstellar environment. If the dust shell is a remnant of the pre-main sequence envelope, the main sequence lifetime of the star sets a lower limit to the sizes of dust grains still present in the surroundings of the star. For Vega a t_{PR} of the order of its main sequence lifetime corresponds to particles larger than 1 mm. On the grounds of these dynamical arguments and because they found that the grains should be larger than 10 μm, Aumann et al. (1984) claimed that the grains are millimeter-sized.

In successive papers Gillett (1986) and Aumann (1991) presented slightly larger numbers for the angular diameter and radius. Their results were based on a more thorough examination of the IRAS POs, both in the in-scan and in the cross-scan direction (Aumann 1991). Aumann (1991) reported that the in-scan and cross-scan sizes of the 60 μm emission are 27 ± 4 arcsec and 34 ± 5 arcsec respectively. These sizes are somewhat larger than the sizes found by Gillett (1986), but they are within the given uncertainties. Aumann (1991) used a two shell model to interpret the IRAS Point Source fluxes and the spatial extent of the 60 μm. He stated that a dust shell model with a radius of 108 AU, dust temperatures $T_1 = 76$ K and $T_2 = 470$ K and grains larger than 100 μm, fits the observational data best. His result confirmed the previous result by Aumann et al. (1984), that the grains around Vega are much larger than interstellar grains.

Following the detection of the IR excess, Vega was observed at various other wavelengths, which are of importance when studying a circumstellar dust shell. We will briefly discuss the consequences of the subsequent observations.

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Harvey et al. (1984) observed Vega at 47 and 95 μm with the Kuiper Airborne Observatory (KAO). They found that the source of this IR emission may be as large as 46 arcsec.

Harper et al. (1984) reported KAO measurements at 193 μm. They showed that the far IR emission declines more rapidly than a Planck spectrum of 85 K at wavelengths longer than 100 μm. They therefore suggest that the emitting particles may be smaller than the millimeter sized objects proposed by Aumann et al. (1984).

Becklin & Zuckerman (1990) presented observations at 0.8 mm. They estimated the total flux of the dust shell at 0.8 mm, taking into account the beam size (16.5 arcsec) and the extent of the 60 μm emission as given by Gillett (1986). The total 0.8 mm flux is consistent with the 193 μm flux as measured by Harper et al. (1984).

Chini et al. (1990) observed Vega at 0.87 and 1.3 mm with a spatial resolution of 9 and 12 arcsec respectively. They modelled the IR excess, assuming the dust shell to extend from 40 to 74 AU, which corresponds to a size of 20 arcsec at 60 μm. Among other things they showed that a dust shell consisting of grains with radii ranging from 2 to 54 μm, will have an excess between 25 and 60 μm in comparison with the observed spectrum of Vega.

This brief overview of observations and models of the IR excess of Vega points out two important facts. First of all, the KAO observations by Harvey et al. (1984) and Harper et al. (1984) disagree with the results deduced from the IRAS data (Aumann et al. 1984; Gillett 1986; Aumann 1991). Secondly, the authors who modelled the observations of the IR excess of Vega, based their models on the size of the 60 μm emission as quoted by Aumann et al. (1984) and Gillett (1986), despite the disagreement between the KAO and IRAS results.

In this *Paper* we investigate the issue of the disagreeing observations of the IR excess of Vega. We re-analysed the IRAS spatial observations, using the GEISHA system (Wesselius et al. 1992) at the Laboratory for Space Research in Groningen. In the next section we will describe in detail the spatial observations of the 60 μm excess and how we determined the angular size of the emitting region. In the third section we will give a rough estimate of the sizes of the particles in the dust shell surrounding Vega. We will discuss the consequences of our results in Sect. 4 and in the last section we will give a summary of our results.

2. Spatial observations with IRAS

In order to examine the extent of the far IR emission of Vega, spatial observations were made with IRAS POs. We analysed the 60 μm POs of Vega in the in-scan direction, during which the satellite was moving at 1/16 of the normal speed (3.85 arcmin s^{-1}). We chose the POs for which the telescope was pointed in such a way that Vega was crossed centrally by detector 15, one of the best behaving detectors at 60 μm. As the sampling rate of IRAS was 8 Hz, a brightness profile of Vega was obtained with a sample separation of 1.8 arcsec. This is a heavy over sampling compared to the nominal IRAS resolution at 60 μm of 1.5 arcmin. To obtain the instrumental beam profile, an identical PO was carried out for a comparison star β Gru, presumably a pure point source. The photospheric 60 μm emission of β Gru is equal to the total 60 μm emission of Vega. This guarantees that the hysteresis of the estimate of the beam profile (β Gru) is similar to the hysteresis of the observation of Vega. The signal to noise ratio of both observations is above 100, as both Vega and β Gru have a large 60 μm flux.

We assumed that the excess emission has a Gaussian shape. We modelled the profile of the excess emission by convolving the point source profile (β Gru) with a Gaussian having a width equal to the extent of the emission of Vega. As the 60 μm emission of Vega also contains a photospheric component (Gillett 1986), the profile of Vega at 60 μm was reconstructed by adding the plain profile of β Gru to the convolved profile of β Gru, after weighting the two profiles with the relative flux contributions of the photosperic and extended emission of Vega, 1.1 and 8.2 Jy respectively. In Fig. 1 the profile of Vega as well as the model profiles for two extreme estimates of the extent of the 60 μm excess are displayed.

The over sampling and high signal to noise ratio of the POs allowed us by visual examination to decide which trial width fits the observed Vega brightness profile best. In Fig. 1 it is shown that a model with a Gaussian width of 30 arcsec is too small, whereas a model with a Gaussian width of 40 arcsec is too large. We therefore conclude that the one dimensional width of the 60 μm emission of Vega in the so called in-scan direction is 35 $\pm$ 5 arcsec.

Aumann (1991) made a comparable study of the extent of the 60 μm emission of Vega in the in-scan direction. He found an angular diameter of 27 $\pm$ 4 arcsec. There is a discrepancy with our in-scan result, arising from the fact that Aumann (1991) neglected the photospheric contribution of Vega. This led to an underestimation of the width of the excess emission. Additionally, Aumann (1991) examined the extent of the 60 μm emission in the cross-scan direction. He found an angular diameter of 34 $\pm$ 5 arcsec. Aumann (1991) once more overlooked the contribution of the photospheric emission. Hence, he also underestimated the cross-scan size of 60 μm emission of Vega. The POs we examined, were not suitable for an analysis of the cross-scan size. Therefore, we do not have an independent estimate of the cross-scan size of the 60 μm emission of Vega.

3. An estimate of the grain sizes

For a spherical dust grain of radius a at a distance $R_{\rm d}$ from the star, the equation of energy balance can be written as

$$\frac{\pi a^2}{4\pi R_{\rm d}^2} 4\pi R_*^2 \int_0^\infty Q_{\rm abs}(\lambda)\pi B_\lambda(T_*)d\lambda = 4\pi a^2 \int_0^\infty Q_{\rm abs}(\lambda)\pi B_\lambda(T_{\rm d})d\lambda \quad (1)$$

The angular diameter $\theta_{\rm d}$, of a thin shell of material in thermal equilibrium can therefore be expressed as

$$\frac{\theta_{\rm d}}{\theta_*} = 0.5 \left(\frac{T_*}{T_{\rm d}}\right)^2 \left(\frac{< Q_{\rm abs,vis} >}{< Q_{\rm abs,IR} >}\right)^{1/2} \quad (2)$$

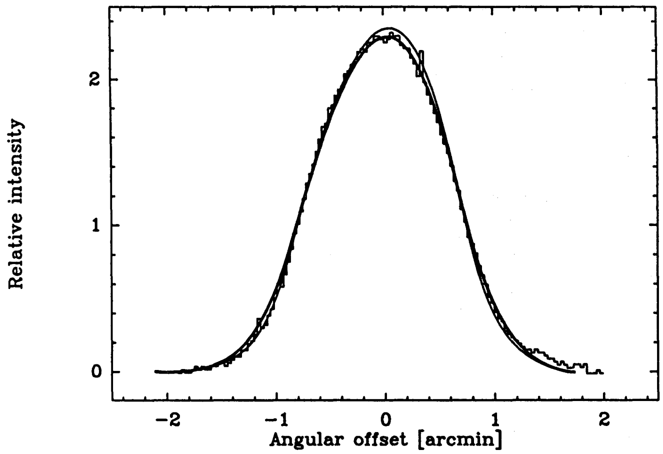

Fig. 1. 60 μm IRAS scan of Vega (histogram) compared with models with a Gaussian width of 30 arcsec (thin line) and of 40 arcsec (thick line)

where

$$< Q_{\rm abs} >= \int_0^\infty Q_{\rm abs}(\lambda)\pi B_\lambda(T)d\lambda \Big/ \int_0^\infty \pi B_\lambda(T)d\lambda \qquad (3)$$

The bulk of the flux of the star is radiated in the visual part of the spectrum and of the dust in the IR part. The flux is absorbed with an efficiency dominated by the $Q_{\rm abs,vis}$ and emitted with an efficiency dominated by the $Q_{\rm abs,IR}$. Adopting a dust temperature $T_{\rm d}$ = 85 K (Aumann et al. 1984), a stellar angular diameter θ_* = 3.2 × 10^{-3} arcsec (Hanbury Brown et al. 1974) and an effective temperature of the star T_* = 9700 K (Dreiling & Bell 1980), we find

$$\theta_{\rm d} = 20.8 \left(\frac{< Q_{\rm abs,vis} >}{< Q_{\rm abs,IR} >}\right)^{1/2} \text{arcsec} \qquad (4)$$

For an angular diameter of the dust shell $\theta_{\rm d}$ = 35 arcsec we then find

$$\frac{< Q_{\rm abs,vis} >}{< Q_{\rm abs,IR} >} \simeq 2.8$$

$Q_{\rm abs,vis}$ is for most materials near unity (Jones & Merrill 1976). Thus, for the particles in the dust shell of Vega $< Q_{\rm abs,IR} >$ is $\sim$ 0.4. In fact, for such values of the absorption efficiency we cannot derive $Q_{\rm abs,IR}$ from the equation of energy balance. $Q_{\rm abs,IR}$ should be derived using Mie theory (van de Hulst 1957).

Nevertheless, one can give a rough estimate of the size of the particles. For grain sizes of the same order as the wavelengths, $\frac{2\pi a}{\lambda} \sim 1$, $Q_{\rm abs}$ is ~ 1. If $Q_{\rm abs} \sim 1$ at 60 μm, the emitting particles should have sizes of the order of 10 μm. $(< Q_{\rm abs,IR} >) < 1$ implies that a significant fraction of the 60 μm flux originates from particles smaller than 10 μm. To find a lower limit for the particle sizes, we use $Q_{\rm abs}$ values as given by Jones & Merrill (1976). For particles of radius 0.1 μm they find that at 40 μm $Q_{\rm abs}$ = 0.007. Assuming $Q_{\rm abs} \propto \lambda^{-1}$, $Q_{\rm abs}$ = 0.0047 at 60 μm, for particles with radii of 0.1 μm. As $< Q_{\rm abs,IR} > \simeq 0.4$, a significant fraction of the flux at 60 μm comes from particles larger than 0.1 μm and smaller than 10 μm.

Because we find that the radius of the dust shell is roughly 1.5 times larger than the value used in previous studies, a simple argument shows that the grains are smaller than determined in earlier studies (> 10 μm). For $Q_{\rm abs} = Q_0\lambda^{-n}$ the temperature of the dust is proportional to $R_{\rm d}^{-2/(n+4)} Q_0^{-(n+4)}$ (van de Hulst 1957). Thus, for the same dust temperature a larger radius of the dust shell can only be reality if Q_0 is smaller than 1, the value found by e.g. Aumann et al. (1984). This implies that the grains are smaller than one originally assumed.

Although Aumann (1991) based his models on a comparable dust shell size, the lower limit for the grain size he found is a factor of 10 larger than our upper limit. We do not understand why his result does not fall within our limits.

We remark here that $< Q_{\rm abs,IR} > \simeq 0.4$ implies that the grains are not radiating as black bodies. Energy distributions of non-black bodies, e.g. dust with $Q_{\rm abs} \propto \lambda^{-n}$, peak at shorter wavelengths than the energy distributions of black bodies at the same temperature. Therefore the temperature as determined by Aumann et al. (1984), which is a colour temperature, is an upper limit of the dust temperature. As a consequence, $< Q_{\rm abs,IR} > \simeq$ 0.4 is a lower limit of the absorption coefficient. This does not alter our rough estimate of the grain sizes. Under the assumption that the dust shell can be represented by a single dust temperature and that it contains only one type of dust, obeying $Q_{\rm abs} \propto \lambda^{-n}$, we find that an energy distribution with $T_{\rm d} \simeq 80$ K and $Q_{\rm abs} \propto \lambda^{-0.15}$ fits both the IR excess and the equation of energy balance of Vega best.

Grains smaller than 10 μm have an energy distribution which declines more rapidly than a Planck spectrum at $\lambda >$ 60 μm. This is in agreement with the result of Harper et al. (1984). It is however, in conflict with the observations around 1 mm (Chini et al. 1990; Becklin & Zuckerman 1990)). Chini et al. (1990) modelled the IR and millimeter observations, assuming an extent of 20 arcsec for the 60 μm emission. They found that if the particle sizes are relatively small (2 - 54 μm), the energy distribution does not fit both the IR and the 1 mm fluxes. Fitting such an energy distribution to the 1 mm observations produces an excess at 25 and 60 μm. Hence, as we find that there must be a significant fraction of the grains smaller than 10 μm, the IR and 1 mm observations can not be explained by one energy distribution. Actually, already the fact that the size of the dust shell at 60 μm is 35 arcsec instead of 20 arcsec (Chini et al. 1990), implies that the observations at 1 mm cannot be fitted simply by extrapolating the energy distribution of the IR excess into the millimeter wavelengths. A larger extent of the 60 μm emission requires a larger correction for the beamsize, when modelling the 1 mm observations. Therefore in the models of Chini et al. (1990) the flux at 1 mm is underestimated. Thus, to model both the IR and the 1 mm observations one needs, in addition to the dust producing the 60 μm excess, a dust component contributing significantly at wavelengths of the order of millimeters, e.g. colder or larger dust grains.

4. Dynamics of the grains

The two major processes that remove grains from the dust shell around Vega are the radiation pressure, blowing grains away from the vicinity of the star and the PR drag, causing grains to spiral into the star. Both processes are proportional to the grain sizes.

Grains will be blown away if the radiation pressure force exceeds the gravitational force

$$< Q_{\rm abs,vis} > \pi a^2 \frac{L_*}{4\pi R_{\rm d}^2 c} > \frac{4}{3}\pi a^3 \frac{GM_*}{R_{\rm d}^2} \tag{5}$$

In other words, if the grains have a radius

$$a(\mu{\rm m}) < 0.6 \frac{< Q_{\rm abs,vis} >}{\rho} \frac{L_*({\rm L}_\odot)}{M_*({\rm M}_\odot)} \tag{6}$$

Assuming $Q_{\rm abs,vis}$ to be 1, L_* is 60 $\rm L_\odot$, M_* is 2.5 $\rm M_\odot$ and using a typical value of 2 g cm^{-3} for the grain density, we find that grains with radii smaller than $\sim$ 10 μm will be blown away from the surroundings of Vega by the radiation pressure.

The remaining grains will be subject to the PR effect. This effect causes grains to spiral into the star on time scales proportional to the radii of the grains, as is described in detail by Burns et al. (1979)

$$t_{\rm PR} = 7.0\ 10^2 \frac{a(\mu{\rm m})\rho R^2({\rm AU})}{< Q_{\rm abs,vis} > L_*({\rm L}_\odot)} \text{ years} \tag{7}$$

Grains located at 140 AU from Vega take $t_{\rm PR} = a \times 4.5\ 10^5$years ($a$, grain radius in μm) to spiral into the star. As Vega has been on the main sequence for roughly 4×10^8 yr, only grains with $a > 1$ mm will have survived the PR drag.

On basis of these dynamical arguments one expects to find only grains with radii larger than 1 mm in the dust around Vega. However, we showed in Sect. 3 that the 60 μm excess can be only explained by the presence of much smaller grains, 0.1 μm $< a <$ 10 μm. We therefore conclude that there is a continuous process going on, which provides the dust shell with small grains.

The small grains could be produced by mass loss from Vega. Hollis et al. (1985) made an attempt to detect such mass loss, using the VLA. They found an upper limit of $3.4 \times 10^{-10}\ \rm M_\odot yr^{-1}$ for the mass loss, which they claimed is not sufficient to replenish the material removed from the dust shell by the radiation pressure and the PR drag.

Alternative processes which could continuously produce small grains are the destruction of larger particles by sublimation and by interparticle collisions, as suggested by Weissman (1984). In fact, such large grains might be producing the 1 mm excess, which remains unexplained by the particles smaller than 10 μm.

5. Summary of the results

1. The angular diameter of the dust shell around Vega is 35 $\pm$ 5 arcsec. This result is in better agreement with the 46 arcsec found by Harvey et al. (1984) than the generally accepted 23 arcsec (Aumann et al. 1984). Using a distance to Vega of 8.1 pc (Jenkins 1963), we find that the radius of the dust shell is 140 AU.
2. A significant fraction of the material of the dust shell of Vega consists of grains larger than 0.1 μm and smaller than 10 μm. This is in agreement with the result of Harper et al. (1984) who found that the far IR emission declines more rapidly than a Planck spectrum at wavelengths beyond 60 μm. This result does not rule out the existence of large grains in the dust shell of Vega. It is however important to note that the presence of millimeter sized grains is not necessary to explain the IRAS observations.
3. There has to be a continuous production of small grains, to replenish the grains which are removed from the circumstellar environment by radiation pressure and PR drag.

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