Is the Vega Debris Disk Evolving in a Steady State?

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Abstract

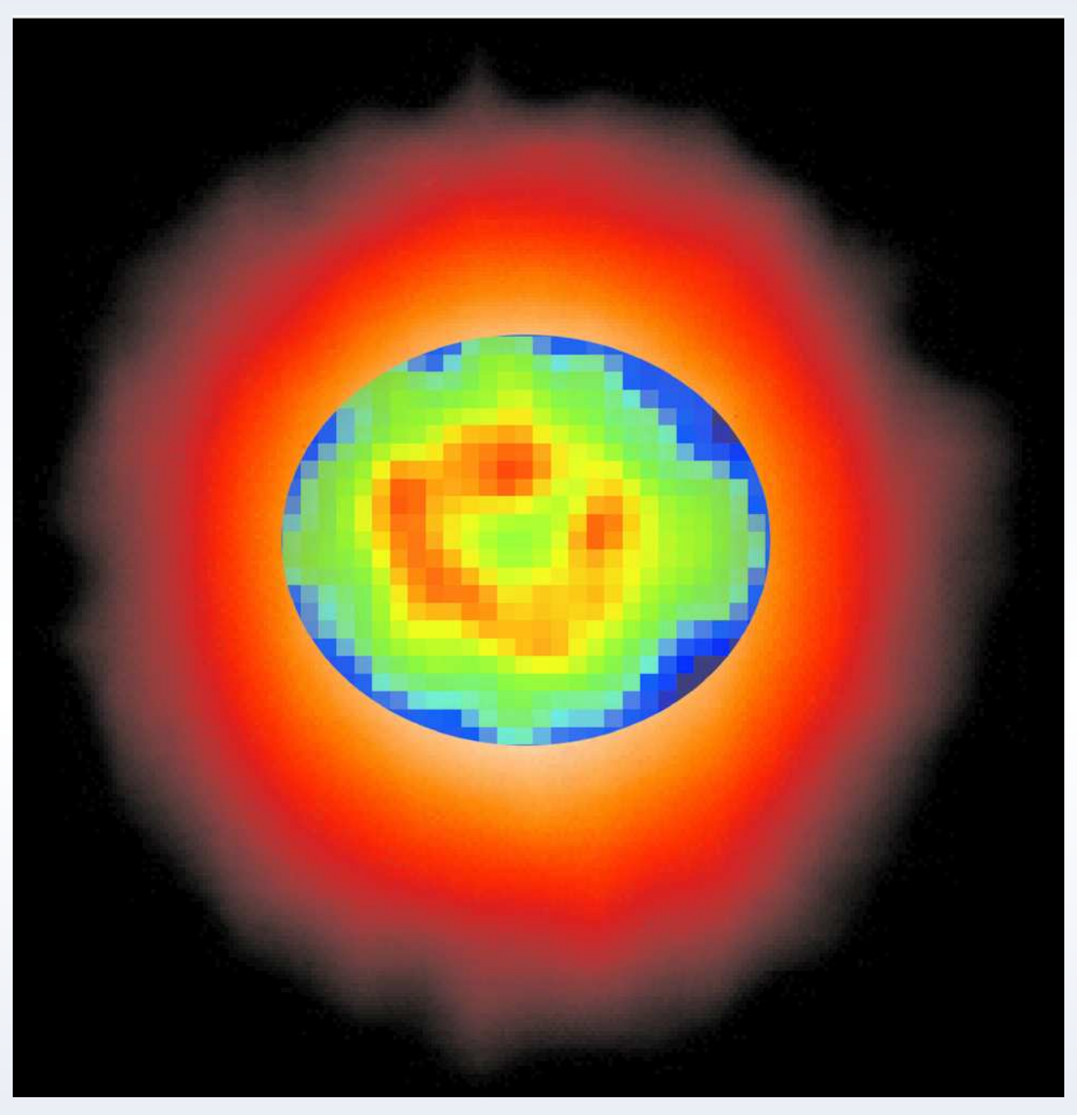
Debris disks, the left-overs of planet formation, consisting of dust and dust-producing planetesimals, are nowadays known to be common around main-sequence stars. The first detection was made around the A0V star Vega in 1984. Since then, that system has been subject of many follow-up investigations. However, it is still under debate which mechanisms drive the production of the observed dust. There have been claims that the standard assumption of a steady-state collisional cascade is not capable of reproducing the observations. To check this, we modeled the Vega disk with our collisional code and calculated the resulting spectral energy distribution (SED) as well as the radial surface brightness profiles for the Spitzer/MIPS wavelengths 24, 70, and 160 µm to compare them to all available observations. We find a reasonable fit both to the observed SED over a broad spectral range from mid-IR to mm and to the brightness profiles. Our conclusion is that the Vega disk does not seem to be incompatible with the standard, steady-state evolutionary scenario.

The Vega System

The Vega disk was resolved with several instruments in the sub-mm region showing a pole-on, clumpy ring [e.g., 8]. As sub-mm emission is dominated by larger, colder grains, the ring probably points to a dust-producing planetesimal belt. Spitzer/MIPS images at 24, 70 and 160 µm revealed a much more extended, featureless, symmetric disk [7]. The interpretation is that the distribution of smaller, hotter dust from the same belt, responsible for the warmer emission, is broadened and smoothed by radiation pressure forces. The composite image on the right-hand side combines the far-IR disk image at 70 µm [7] with the sub-mm one at 350 µm [8].

Vega is known to be a fast rotator [5, 6]. Thus, the stellar properties seen by the disk differ from those that are seen by the observer. The table below lists key parameters of the star:

	equator	pole
$R^{[5]}[R_\odot]$	2.873 ± 0.026	2.306 ± 0.031
$T_{\rm eff}^{[6]}[K]$	$7\,900^{+500}_{-400}$	$10\,150 \pm 100$
$L_*[L_\odot]$	28^{+8}_{-6}	57 ± 3
$\log(g[cm/s^2])^{[5]}$	4.074 ± 0.012	3.589 ± 0.056
$M_*^{[6]}[M_\odot]$	2.3 ± 0.2	
Age[Myr]	350	



Approach

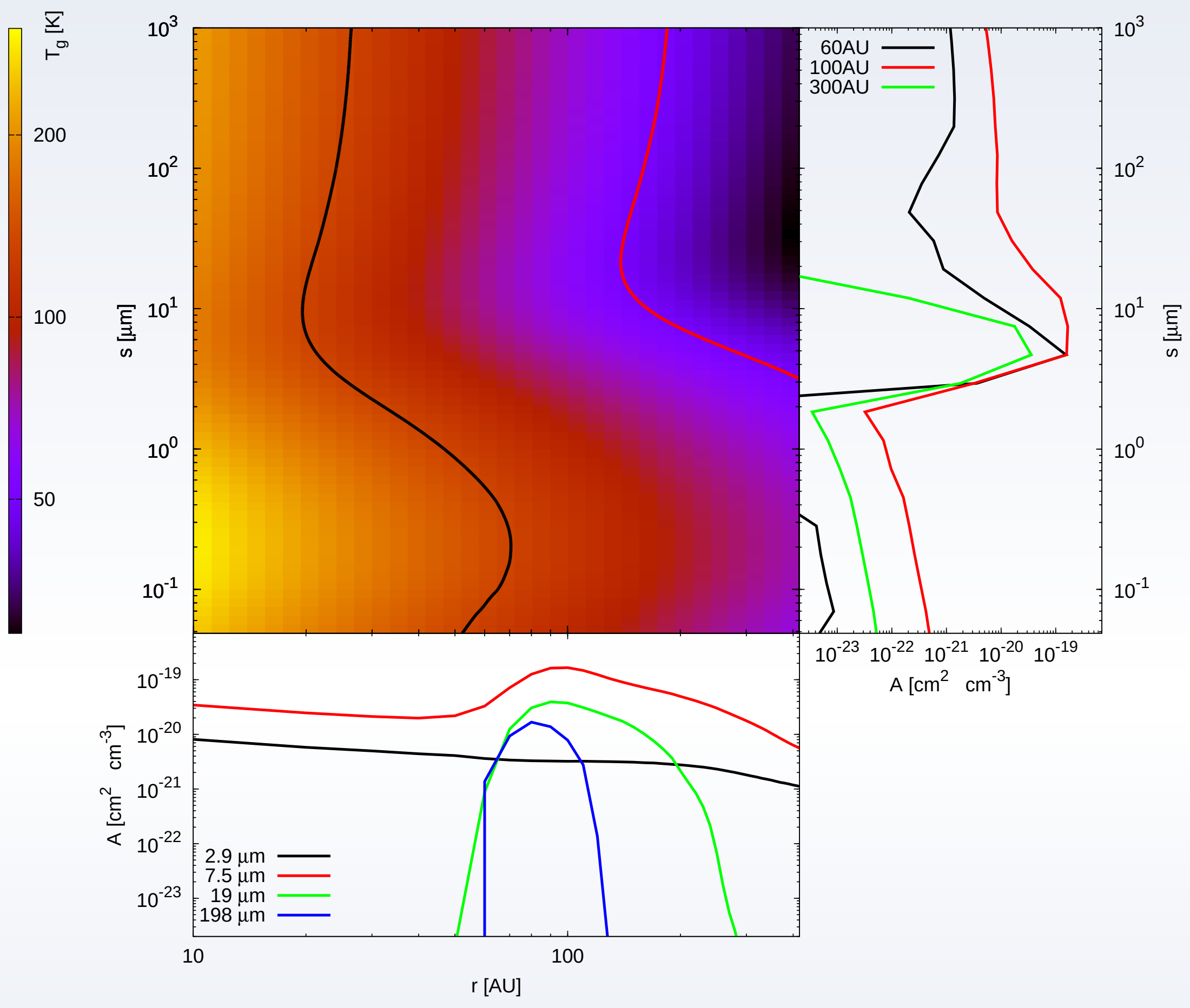
To reproduce the observational data, we consecutively employ three numerical tools:

ACE: Analysis of Collisional Evolution
A collisional code to generate a debris disk from an assumed ring of planetesimals and then to follow the evolution of the size and spatial distribution of all solids in the disk, from planetesimals to dust [1, 2].

SEDUCE: SED Utility for Circumstellar Environment
Assuming the particles to be in thermal equilibrium with the stellar radiation, the code calculates the spectral energy distribution (SED), from the dust portion of the modeled disk. Using appropriate scaling laws [3], the calculated SED can be scaled to the observed one.

SUBITO: SUrface Brightness Investigation TOol
A code that calculates the radial surface brightness profile and convolves it with the stellar point spread function (PSF). The resulting profile is then compared to the observed one. If resolved observations are available (which is the case for the Vega disk), a combined analysis of SED and brightness profiles allows us to break some of the degeneracies known to be typical of the SED fitting.

It is not to be expected that a first guess of model parameters will lead directly to a perfect match with the observations, so that the whole simulation (ACE-SEDUCE-SUBITO) has to be repeated with different model parameters. To get an impression of how the model has to be modified we compare the dust distribution with the temperature profile to see which regions in the grain size and spatial distribution need to be altered. Such a comparison for our “nominal” model 1 (see table on the right) is shown in the figure.

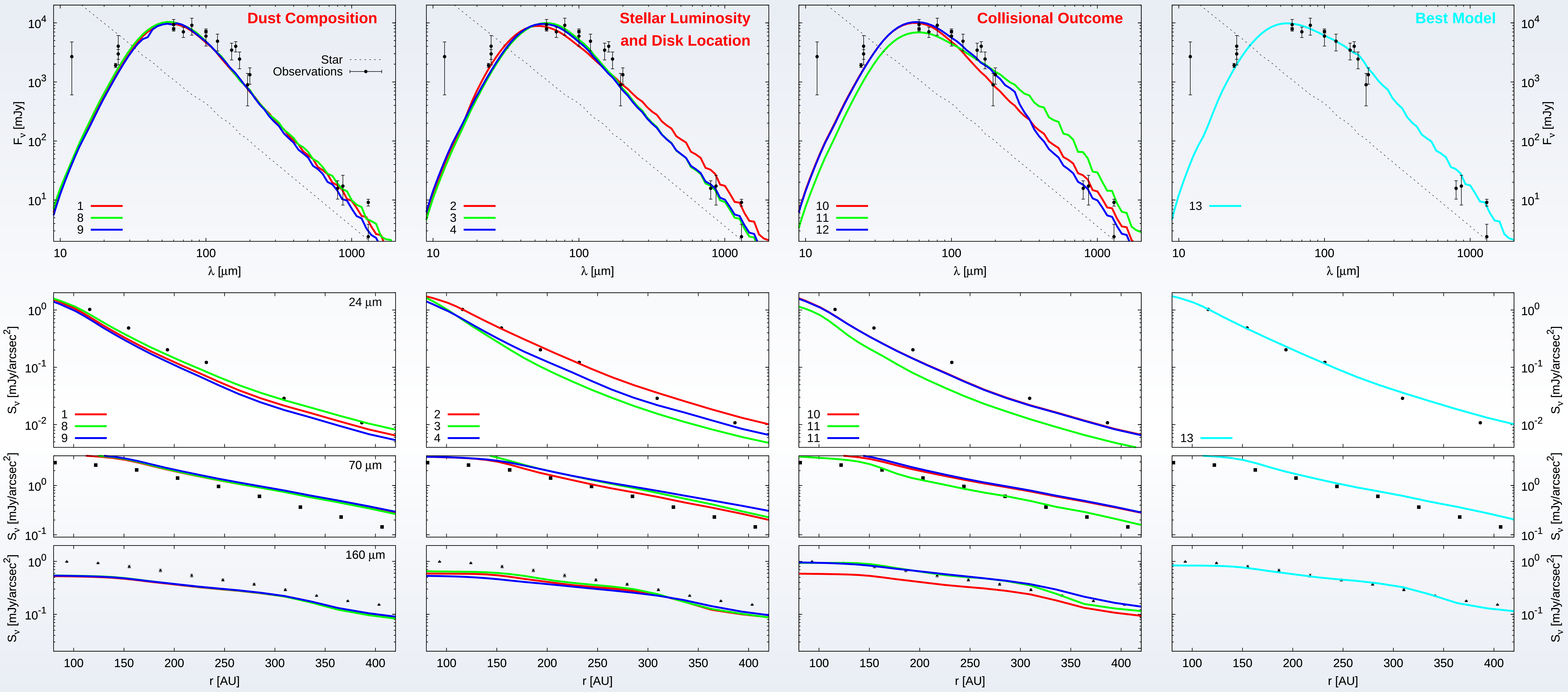


Models

Model 1 is our first-guess, “nominal” model. In the others, we vary: stellar luminosity; location, extension, excitation, and thickness of the disk; dust composition; collisional outcome prescription. Models 2 and 13 assume a reduced luminosity at the stellar equator, as expected for a rapidly rotating star. The nominal grain model is based on Mie calculations for astronomical silicate [9]. For models 8 and 9, we applied Maxwell-Garnett theory to produce inhomogeneous grains with 10% iron or water ice inclusions embedded in an astrosil matrix. The nominal collisional prescription includes disruptive and cratering collisions [3]. In model 10 the cratering efficiency was lowered; in model 11 only destructive collisions were considered. The maximum in the size distribution in model 12 was broadened artificially to emulate an expected scatter of optical and mechanical properties of grains in a realistic disk.

model	$L_*[L_\odot]$	a_{inner}[AU]	a_{outer}[AU]	e_{max}	$\sin\epsilon$	composition	collisional outcome
1	37	70	100	0.2	0.1	astrosil	nominal case
2	**25**	70	100	0.2	0.1	astrosil	nominal case
3	37	**50**	100	0.2	0.1	astrosil	nominal case
4	37	70	**120**	0.2	0.1	astrosil	nominal case
5	37	**50**	**120**	0.2	0.1	astrosil	nominal case
6	37	70	100	**0.1**	**0.05**	astrosil	nominal case
7	37	70	100	**0.4**	**0.2**	astrosil	nominal case
8	37	70	100	0.2	0.1	**iron incl.**	nominal case
9	37	70	100	0.2	0.1	**ice incl.**	nominal case
10	37	70	100	0.2	0.1	astrosil	**weak crat.**
11	37	70	100	0.2	0.1	astrosil	**no crat.**
12	37	70	100	0.2	0.1	astrosil	**smoothed size distr.**
13	**25**	70	100	0.2	0.1	astrosil	**smoothed size distr.**

Results



Conclusions

We have modeled a steady-state collisional evolution of the Vega debris disk, calculated its thermal emission, and compared the results with available resolved observations and photometry. Our first-guess model revealed two discrepancies: (1) a lack of 24 µm emission and (2) a too steep drop in the SED in the far-IR. Accordingly, we varied the stellar luminosity, the chemical composition of dust, the disk's location and extension (within reasonable limits), its dynamical excitation, and the model of collisional outcomes. We find that neither the chemical composition nor the disk parameters can alter the emission properties significantly. In contrast, the adopted stellar luminosity and the collisional outcome prescription both have noticeable impact on the results. For instance, inclusion of cratering collisions seems mandatory to correctly reproduce the observed sub-mm emission.

Assuming a reduced stellar luminosity, as expected at the equator of the rapidly rotating star, fixes the problem (1) with the lacking 24 µm emission. To overcome the problem (2), a steep drop in the far-IR, we need a broader size distribution around its maximum. We speculate that a broader size distribution could result, for instance, from a scatter in optical and mechanical properties of dust particles in a realistic disk. We mimick the effect by artificially broadening the size distribution to show that the problem (2) can indeed be eliminated.

We conclude that the debris disk of Vega seems to be compatible with a standard, steady-state evolution scenario.

References

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