Modelling Interstellar Extinction Using Aggregate Dust Model

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ABSTRACT

In this work, we consider the aggregate dust model to study the extinction efficiency (Q_{ext}) of interstellar dust in the wavelength range 0.11 - 3.4 µm. Using Superposition T-matrix code with Ballistic Cluster-Cluster Aggregate (BCCA) having 64 number of monomers and a well defined size distribution within a size range 0.004 to 0.25 micron, the normalized average extinction curves are generated for astronomical silicate, graphite and amorphous carbon. The well pronounced UV bump can be noticed for graphite grains at 2175Å. It is observed that for large size of the graphite grain, the UV-bump almost disappear. Moreover the nature of variation of extinction curve with increasing size of the grain is also studied. We then try to regenerate the observed extinction curve in the wavelength range 0.11 - 3.4 µm considering suitable mixing among silicate, graphite and amorphous carbon. It is found from our work that the observed interstellar extinction curve can be successfully reproduced using the proposed aggregate dust model with 45% silicate, 40% graphite and 15% amorphous carbon in the total mixture.

Extinction (in general):

- Extinction refers to the sum of absorption and scattering and is generally determined by comparing observations of reddened and unreddened stars assumed to have identical intrinsic energy distributions.

- The spectral dependence of extinction, or extinction curve, is a function of the composition, structure and size distribution of the particles.

- The study of interstellar extinction is important because they provide essential information for understanding the properties of the dust.

- The general extinction A_λ is given by (Spitzer 1978, JRASC, Vol. 72, p.349):

$$A_\lambda = -2.5 \log \left[\frac{F(\lambda)}{F_0(\lambda)} \right] = 1.086\, N_d\, Q_{ext}\, \sigma_d,$$

where $F(\lambda)$ and $F_0(\lambda)$ are the observed and expected fluxes, N_d is the dust column density, Q_{ext} is the extinction efficiency factor, and σ_d is the geometrical cross-section of a single particle.

- The observational determination of the general extinction, A_λ, is very difficult and it is therefore general practice to normalize extinction data at B and V photometric bands (Jones 1988, MNRAS, 234, 209), e.g.

$$\frac{E(\lambda - V)}{E(B - V)} = \frac{A_\lambda - A_V}{A_B - A_V} = \frac{A_\lambda}{E(B - V)} - R,$$

- For 'normal' extinction E(B-V) = 0.6 mag kpc^{-1} and R=3.1

The observed interstellar extinction curve:

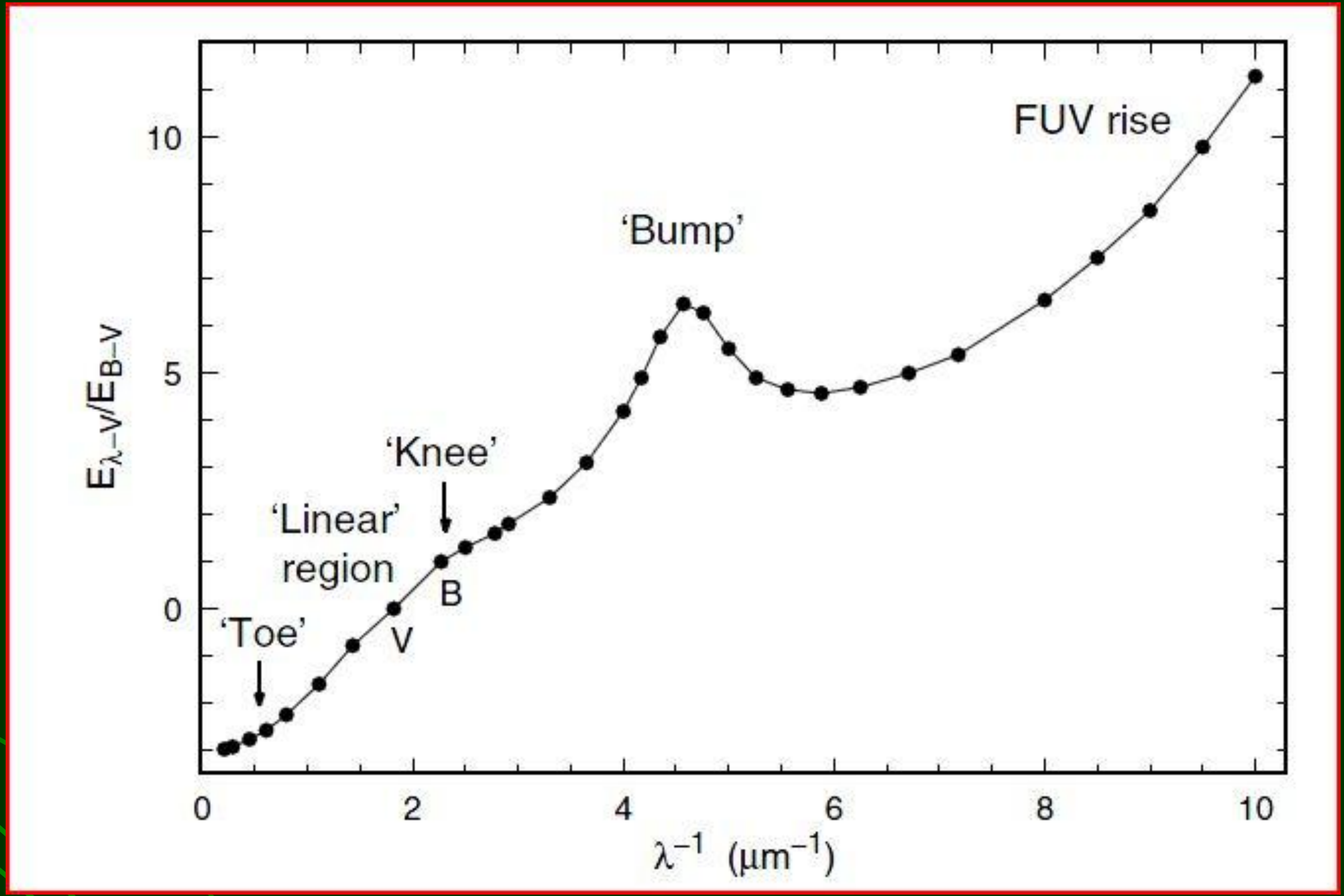


Fig-1: The observed average interstellar extinction curve ($E_{\lambda-V}/E_{B-V}$ versus λ^{-1}) in the spectral range 0.2—10 μm^{-1} (Ref: Whittet et al. 2003, in dust in the Galactic Enviornment, 76, 2nd edition ; UK: IOP Publising Ltd.)

- Using compact spheroidal particles, attempt has been made to study the extinction properties of interstellar dust (Gupta et al. 2005, Voshchinnikov et al. 2004, Das et al. 2010b etc.).

- Recent studies of interplanetary and cometary dust indicate that cosmic grains are likely to be porous, fluffy and composites of many small grains coalesced together, due to grain-grain collisions, dust-gas interactions and various other processes.

- These grains appear to consist of units (monomers) whose sizes are tens of nanometers. Monomers can aggregate into fluffy particles with typical sizes 0.1–10 μm.

- Assuming an individual cometary grain to be an aggregate of several monomers, several investigators studied the light scattering properties of cometary dust (Kimura et al. 2006, Bertini et al. 2007; Das et al. 2008a, 2008b, 2010a; Paul et al. 2010 etc).

- Das et al. (2008a, 2008b) analyzed the observed polarization data of Comet C/1990 K1 Levy and Comet C/1995 O1 Hale-Bopp, and successfully reproduced the polarization curve through simulations.

- Using Discrete Dipole Approximation (DDA), several investigators studied the extinction properties of the porous composite grains (Wolff et al. 1994, 1998; Voshchinnikov et al. 2006; Vaidya & Gupta 1999; Vaidya et al. 2007, 2009 etc.).

- However aggregate dust model can be also used to study the extinction properties of porous dust grains.

- Considering cosmic dust as aggregates of amorphous carbon and astronomical silicates, Iati et al. (2004, ApJ, 615, 286.) calculated extinction, scattering, and radiation pressure cross sections using Superposition Transition Matrix approach.

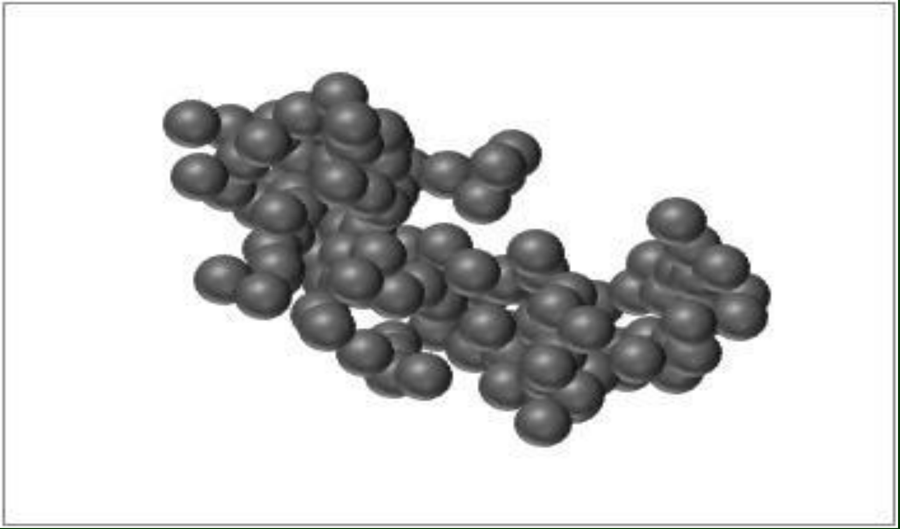
- Iati et al(2004) took aggregate dust model to explain interstellar extinction in general. But, they did not consider the size distribution of cluster. Their approach was not based upon to explain the average extinction curve using a suitable size distribution.
- In the present work, grain aggregates are assumed to be fluffily substructured collections of very small particles loosely attached to one another. Each particle is assumed to consist of a single material, such as silicates or carbon, as formed in the various separate sources of cosmic dust.
- The main objectives of the present work is to study the extinction efficiencies in the wavelength region, 0.11 - 3.4μm of the graphite, amorphous carbon and silicate grains with various sizes which are typical to interstellar grain sizes.
- These materials have been the ingredients for most of the models used in the previous work (Mathis et al. 1977; Draine & Lee 1984; Weingartner & Draine 2001, Gupta et al. 2005, Vaidya et al. 2007 etc.).

- **Using the extinction efficiencies of the aggregate particles with a power law type grain size distribution, we compute the average interstellar extinction curves for graphite, amorphous carbon and astronomical silicate.**

- **We then try to reproduce the observed extinction curve by suitable mixing among them.**

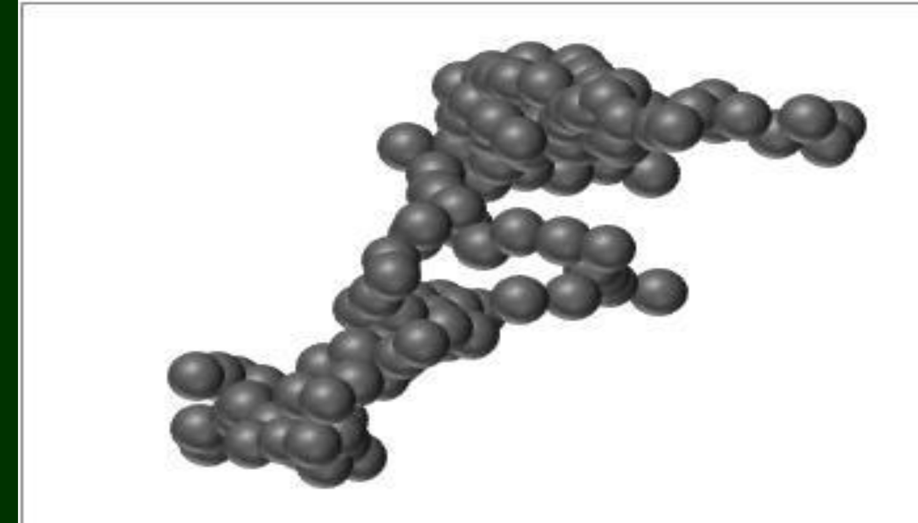
Aggregate Dust Model:

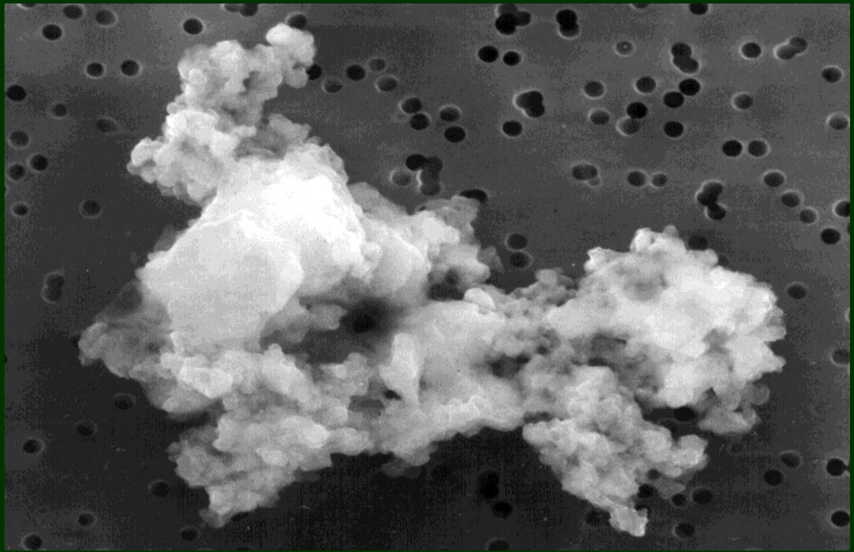
- In our computations, we build our aggregates using ballistic aggregation procedure.
- We adopt two different models of cluster growth: first via single-particle aggregation and then through cluster–cluster aggregation. These aggregates are built by random hitting and sticking particles together.
- When the procedure allows only single particles to join the cluster of particles, the aggregation is called Ballistic Particle-Cluster Aggregate (BPCA).
- If the procedure allows clusters of particles to stick together, the aggregate is called Ballistic Cluster–Cluster Aggregate (BCCA).



← BPCA

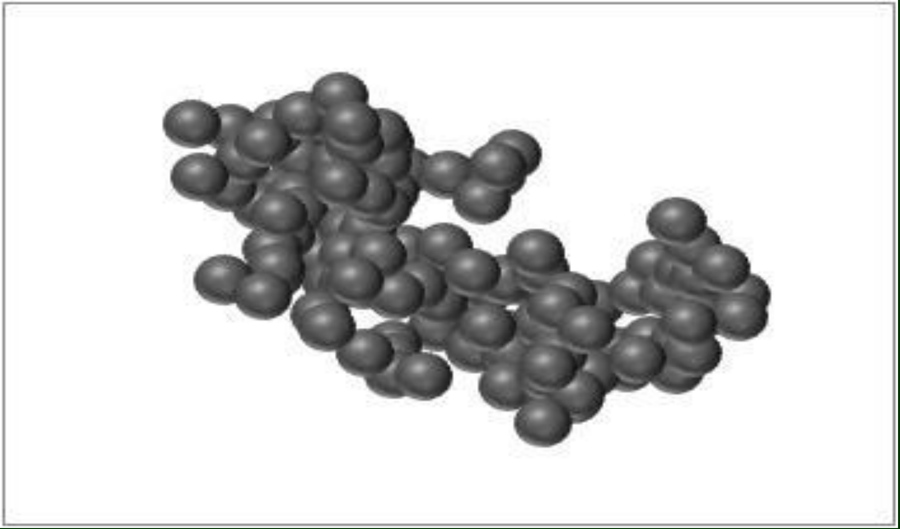
BCCA →



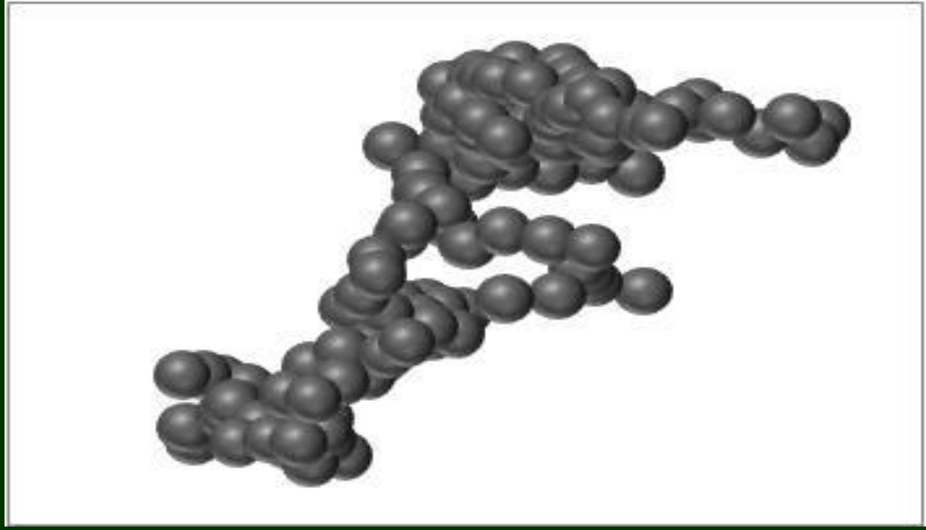


← IDP

It is to be noted that the structure of these aggregates are similar to those of *Interplanetary Dust Particles* (IDP), often get collected at high altitudes of the Earth's atmosphere.



BPCA structure with 128 monomers



BCCA structure with 128 monomers

- The porosity of the aggregate is defined as

  $P = 1 - (V_i / V)$, where, $V_i = N[(4/3)\pi a_m^3]$,

  V being the volume of the sphere with apparent radius of the aggregate (a_c) and a_m is the radius of the individual monomer (i.e. sphere).

→ Usually BCCA particles are more porous than BPCA particles.

→ In the present study, the porosity of BPCA and BCCA particles of 128 monomers has the values 0.90 and 0.94, respectively.

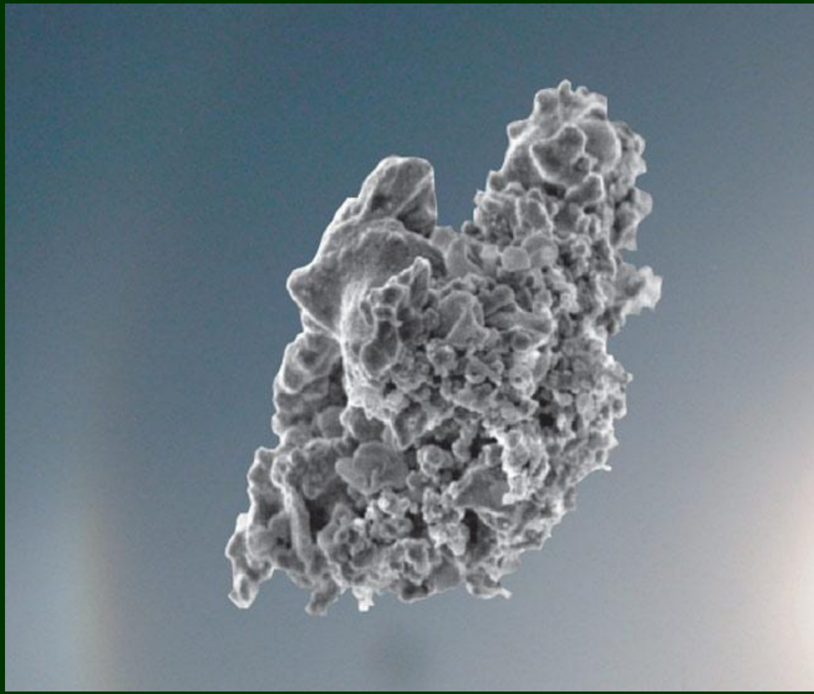
→ The fractal dimension of BPCA and BCCA is *D ≈ 3 and 2*, respectively.

Composition:

- Interstellar dust mainly consist of five heavy elements C, O, Mg, Si, Fe . The carbonaceous and silicate particles are likely materials to contain the above mentioned elements.

- Therefore we consider submicron particles of amorphous carbon, graphite and astronomical silicates to be the most likely composition to explain the nature of average extinction curve.

- In our computation we take the refractive indices of graphite and astronomical silicate particles from Draine (1985, ApJS, 57, 587) and amorphous carbon from Rouleau & Martin (1991, ApJ, 377, 526).



The number of monomers:

- The number of the monomers in the present study are taken to be N = 8, 16, 32 and 64, respectively.

- In our computation, the maximum number of monomer is restricted to 64 because of long computational time and memory.

- Actually, it is seen that the increase of number of monomer does not change the extinction efficiency value appreciably if one consider the large number of monomers (Iati et al. 2005, Journal of Physics: Conference Series, 6, 149).

- The radius of an aggregate particle can be described by the radius of a sphere of equal volume given by $a_v = a_m N^{1/3}$, where N is the number of monomers in the aggregate.

	a_v (μm)			
N	$a_m = 0.10$ μm	$a_m = 0.11$ μm	$a_m = 0.12$ μm	$a_m = 0.13$ μm
32	0.32	0.35	0.38	0.41
64	0.40	0.44	0.48	0.52
72	0.42	0.46	0.50	0.54
80	0.43	0.47	0.52	0.56
96	0.46	0.50	0.55	0.59
128	0.50	0.55	0.60	0.65

- Laboratory diagnosis of particle coagulation in the solar nebula suggests that the particles grow under BCCA process (Wurm & Blum 1998, Icarus, 132, 125). As a consequence of this, the numerical computation in the paper has been done with BCCA particles.

The size of monomers:

- The size of the individual monomer in a cluster plays an important role in scattering calculations.
- The most of the work related to interstellar extinction considered a power law grain size distribution :

$$n(a) \sim a^{-3.5}$$

- This is famous Mathis, Rumpl & Nordsieck (MRN) size distribution with a normal size range of 0.005 to 0.250 μm.
- The above size range and distribution provides a reasonable fit to the observed average interstellar extinction curve.
- To study the effects of a_m, we ran simulations with $0.001 \leq a_m \leq 0.062$ μm (with a step size of 0.001 μm), i.e., $0.004 \leq a \leq 0.25$ μm.
- In our work, we use the MRN power law grain size distribution (Mathis et al. 1977, ApJ, 217, 425) to generate the average interstellar extinction curves for graphite, amorphous carbon and silicate grains.

Scattering theory:

- **Mie theory (for spherical particles)**
- **Discrete Dipole Approximation (DDA)**
- **Transition Matrix (T-matrix) theory**
  - **General T-matrix code (for compact non-spherical particles)**
  - **Superposition T-matrix code (for cluster of spheres or aggregates)**

T-matrix theory

- The T-matrix method is a powerful exact technique for computing light scattering by single, homogeneous spheroidal particles based on numerically solving Maxwell's equations.

- This method was initially introduced by Waterman (1971, Phys. Rev. D, 1971, 3, 825). It is used to determine the scattering by **compact spheroidal dust particles.**

- Later, Mackowski & Mishchenko (1996, JQSRT, 13, 2266) developed the *Superposition T-matrix* method for ensemble of spheres (aggregates).

Numerical computation:

In our simulation, we divide the present work into two phases:

- We first generate the average extinction curves for astronomical silicate, graphite and amorphous carbon in the wavelength range 0.11 μm - 3.4 μm, where MRN size distribution with size range 0.004 - 0.248 μm is taken in steps of 0.004 μm.
- We then consider a mixture of astronomical silicate, graphite and amorphous carbon in the total mixture to reproduce the observed interstellar extinction curve in the wavelength range 0.11- 3.4 μm.

- The free parameters used in the model are the contribution of astronomical silicate, graphite and amorphous carbon in the total mixture. In our work, the parameter 'α' corresponds to silicate contribution in the total mixture; 'β' and 'γ' correspond to contribution of graphite and amorphous carbon in the total mixture respectively, where $\alpha + \beta + \gamma = 1$.

- We use χ^2- minimization technique to evaluate the best fit values of the above free parameters by the following equation:

$$\chi^2_{ext} = \frac{\sum_{i=1}^{N} \mid \mathbf{T}_{obs} - \mathbf{T}_{theo} \mid^2}{\mathbf{NN}}$$

Here, N is the number of wavelength points of the extinction curve and NN is the degrees of freedom. T_{obs} is the observed extinction at different wavelengths (0.11 - 3.4 μm) and T_{theo} is the corresponding extinction efficiency obtained from model calculation.

Results and discussion:

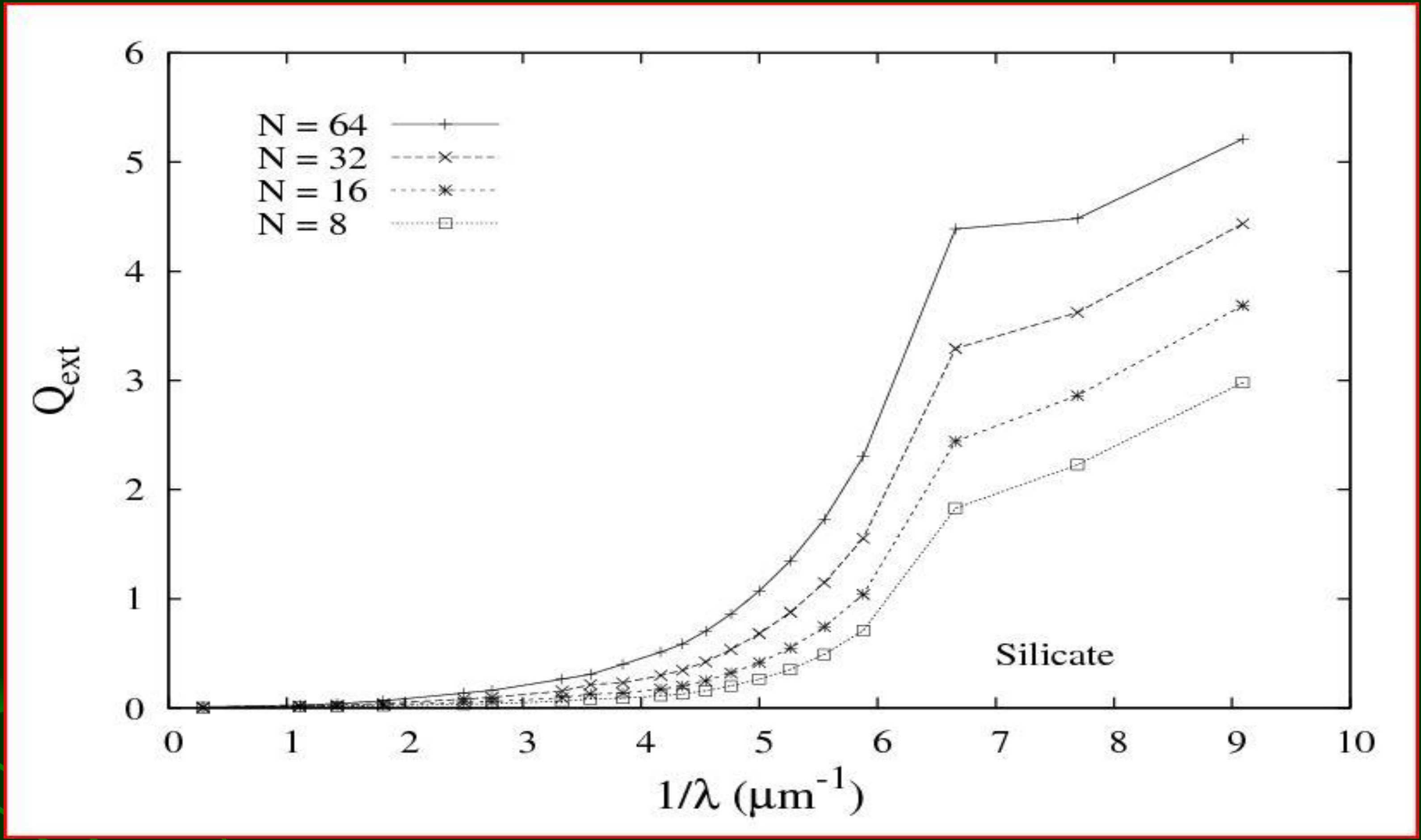


Fig.2: Effect of N on extinction efficiency (Q_{ext}). The simulated extinction efficiency curves obtained for BCCA silicate aggregates are drawn with N = 8, 16, 32 and 64. Here, the size of the monomer (a_m) is 0.013μm.

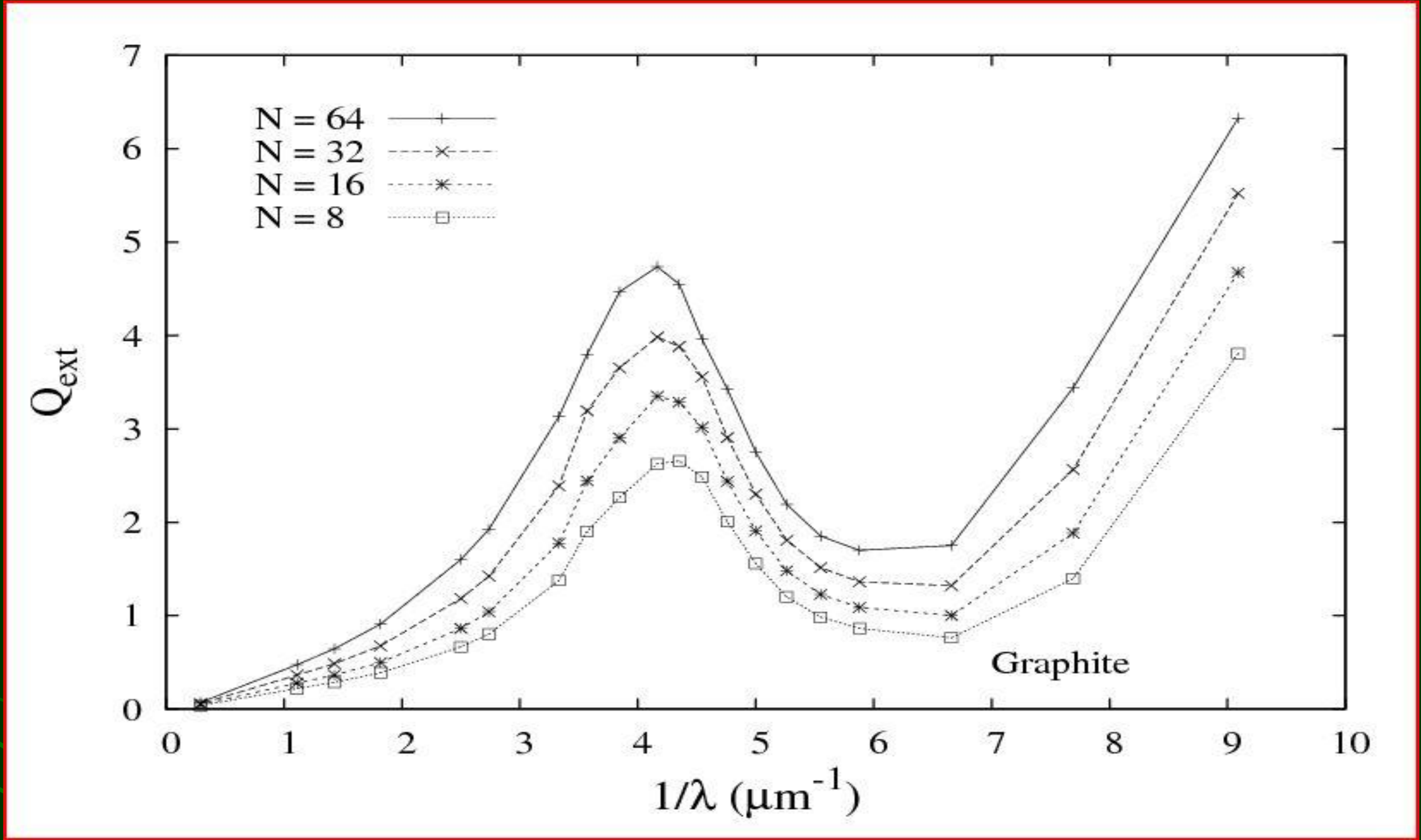


Fig.3: Effect of N on extinction efficiency (Q_{ext}). The simulated extinction efficiency curves obtained for BCCA graphite aggregates are drawn with N = 8, 16, 32 and 64. Here, the size of the monomer (a_m) is 0.013μm.

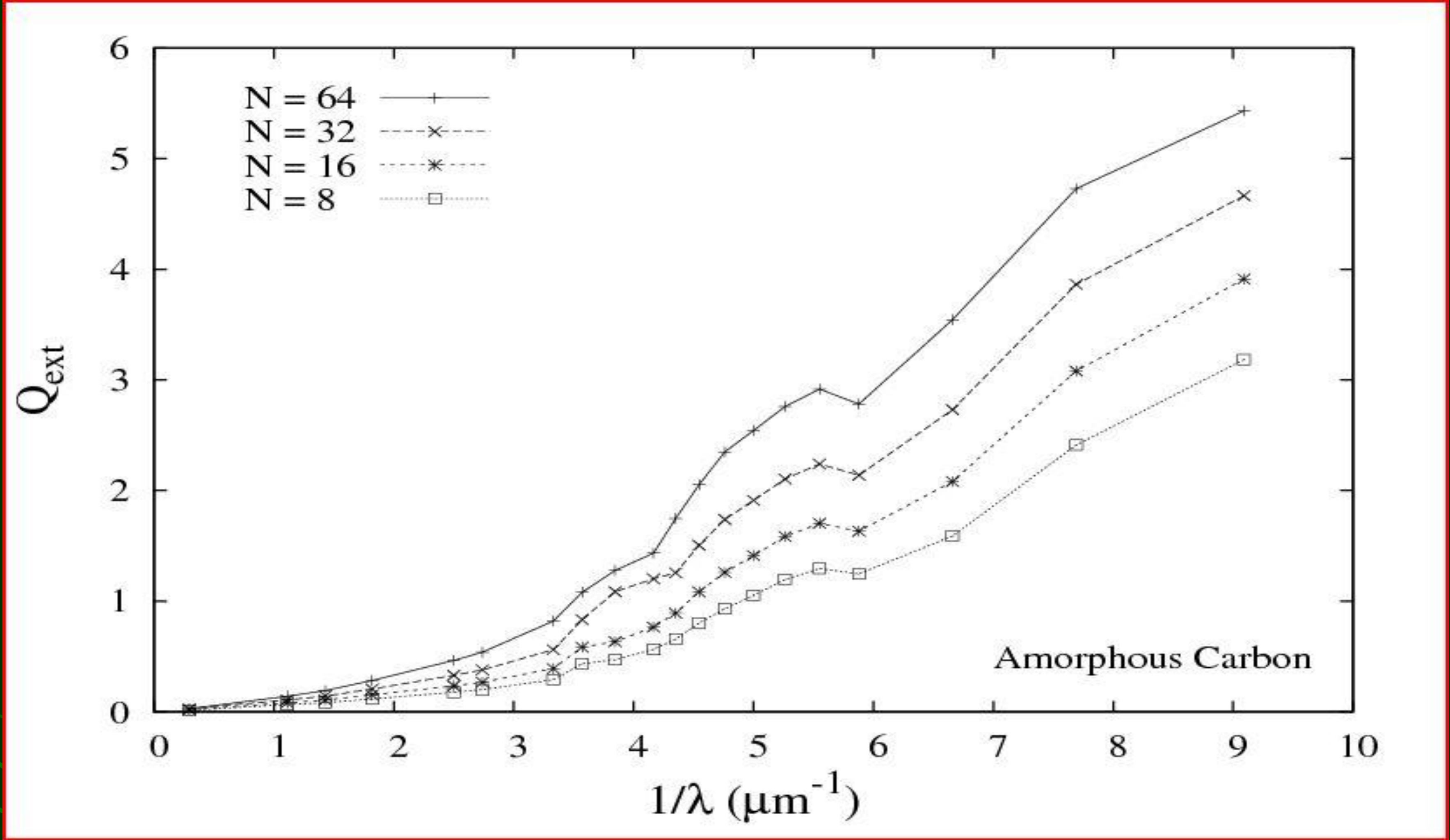
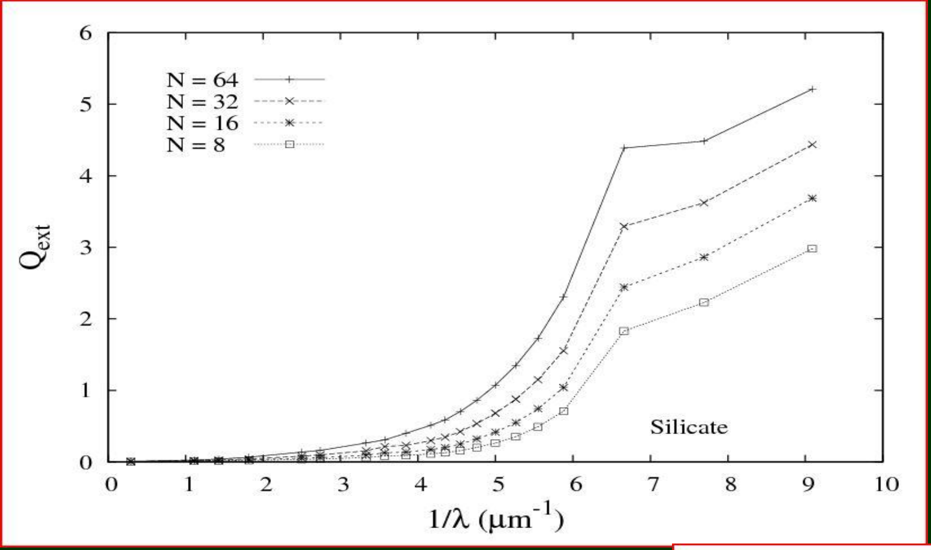
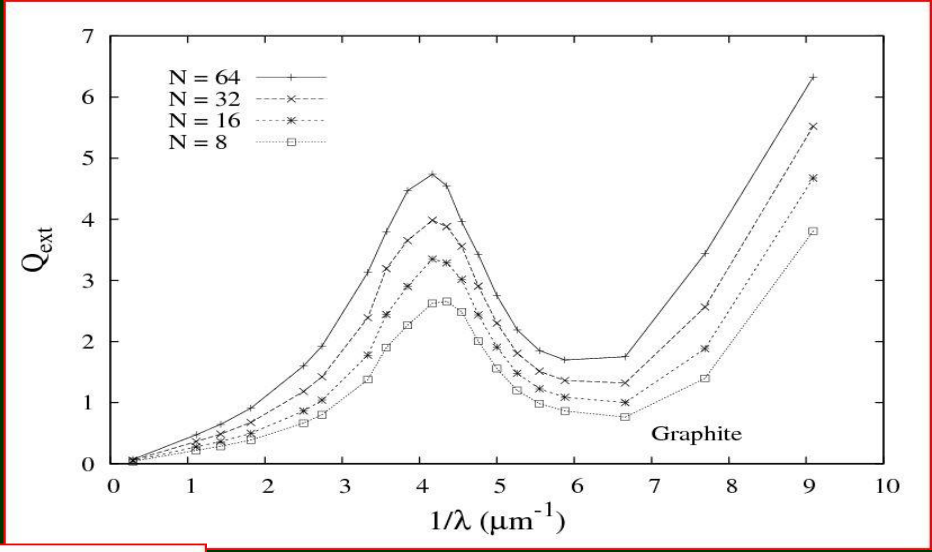
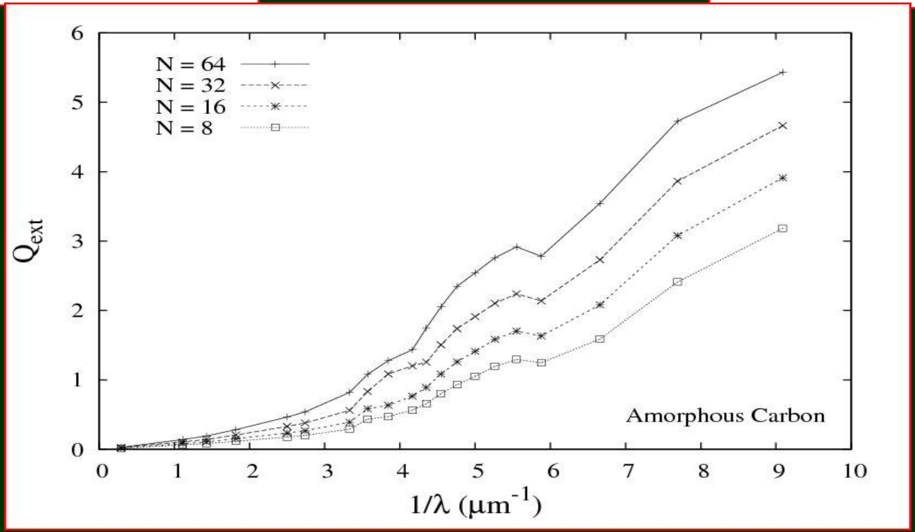


Fig.4: Effect of N on extinction efficiency (Q_{ext}). The simulated extinction efficiency curves obtained for BCCA amorphous carbon aggregates are drawn with N = 8, 16, 32 and 64. Here, the size of the monomer (a_m) is 0.013μm.







It can be seen from the figures that Q_{ext} increases with the increase of number of monomers, i.e., with the increase of cluster size.

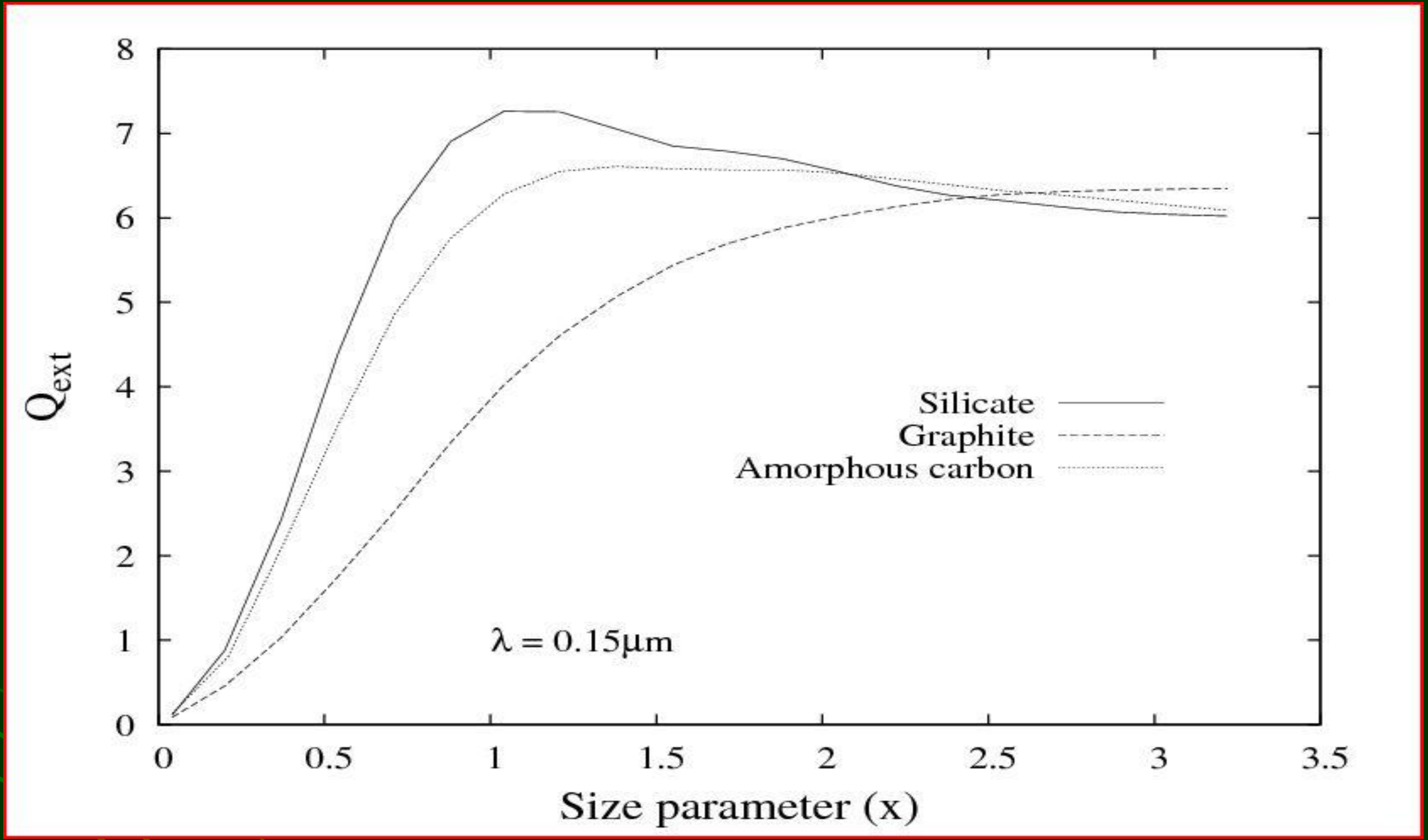


Fig.5: The variation of extinction efficiency (Q_{ext}) with size parameter of the monomer ($x = 2\pi a_m/\lambda$) for silicate, graphite and amorphous carbon at $\lambda = 0.15\mu m$.

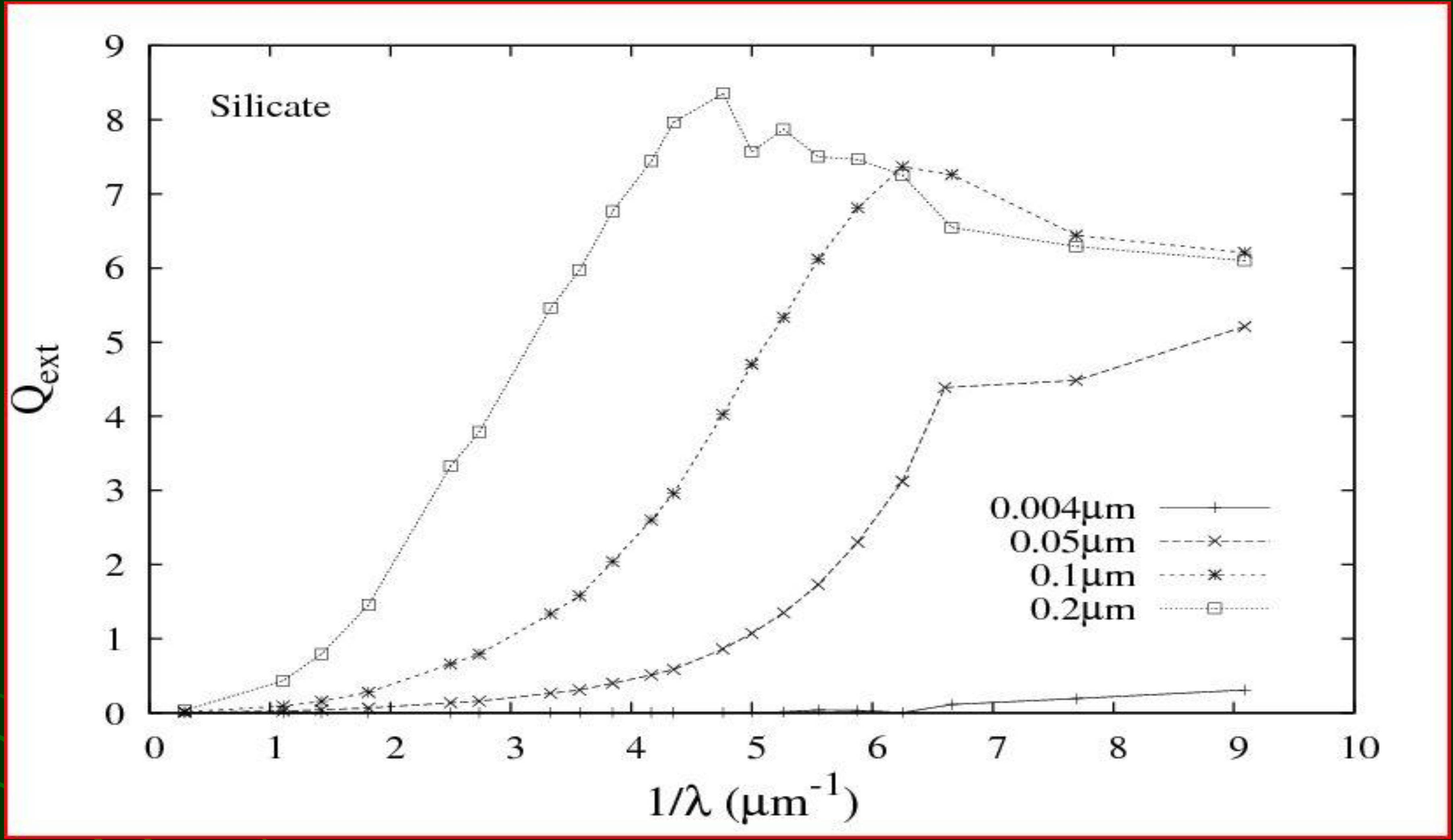


Fig.6: **Extinction efficiencies Q_{ext} versus 1/λ for randomly oriented silicate grains of sizes a = 0.004, 0.05, 0.1 and 0.2 μm in the wavelength range 3.4 to 0.11 μm.**

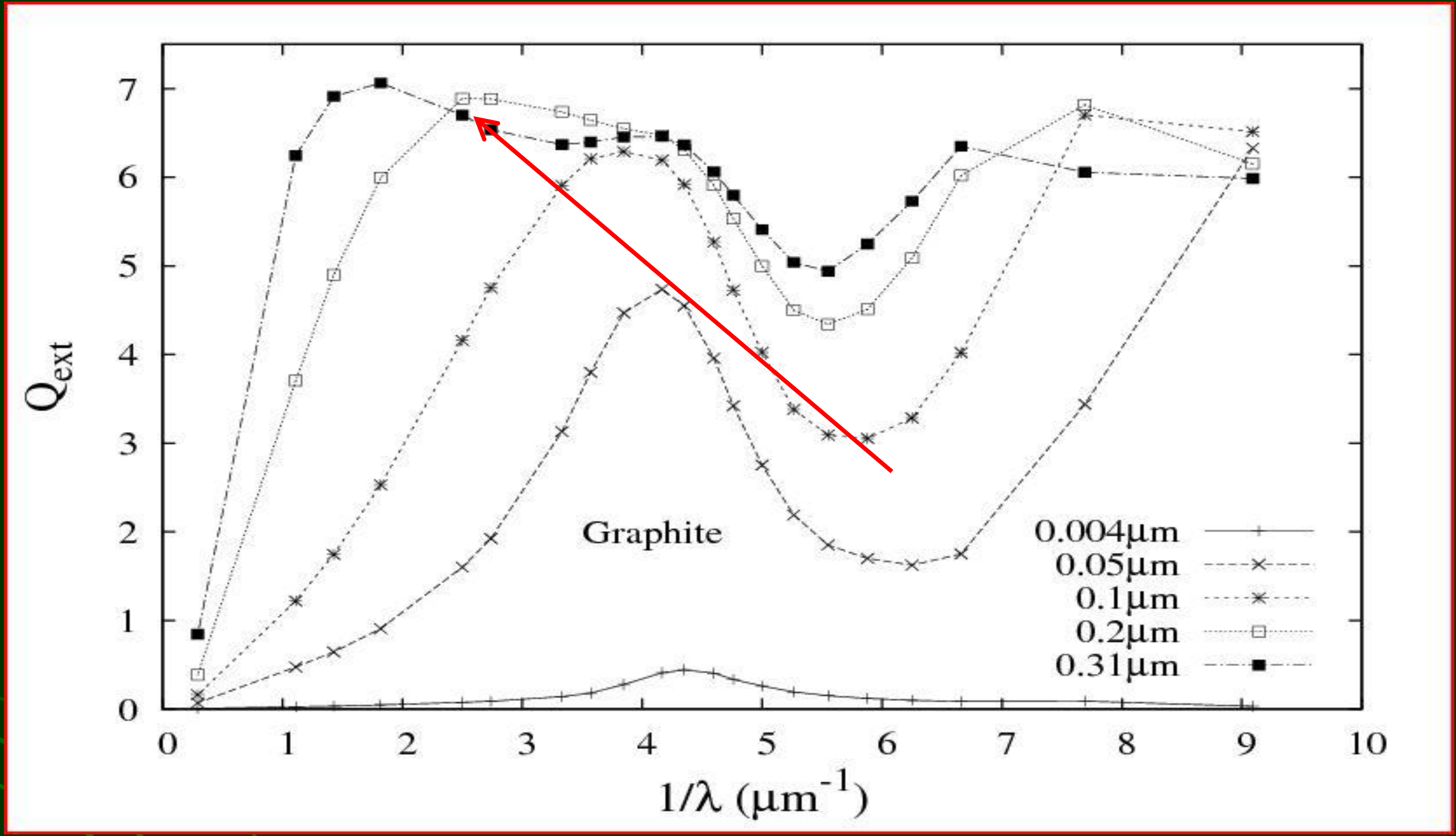


Fig. 7: Extinction efficiencies Q_{ext} versus 1/λ for randomly oriented graphite grains of sizes a = 0.004, 0.05, 0.1 and 0.2 μm in the wavelength range 3.4 to 0.11 μm.

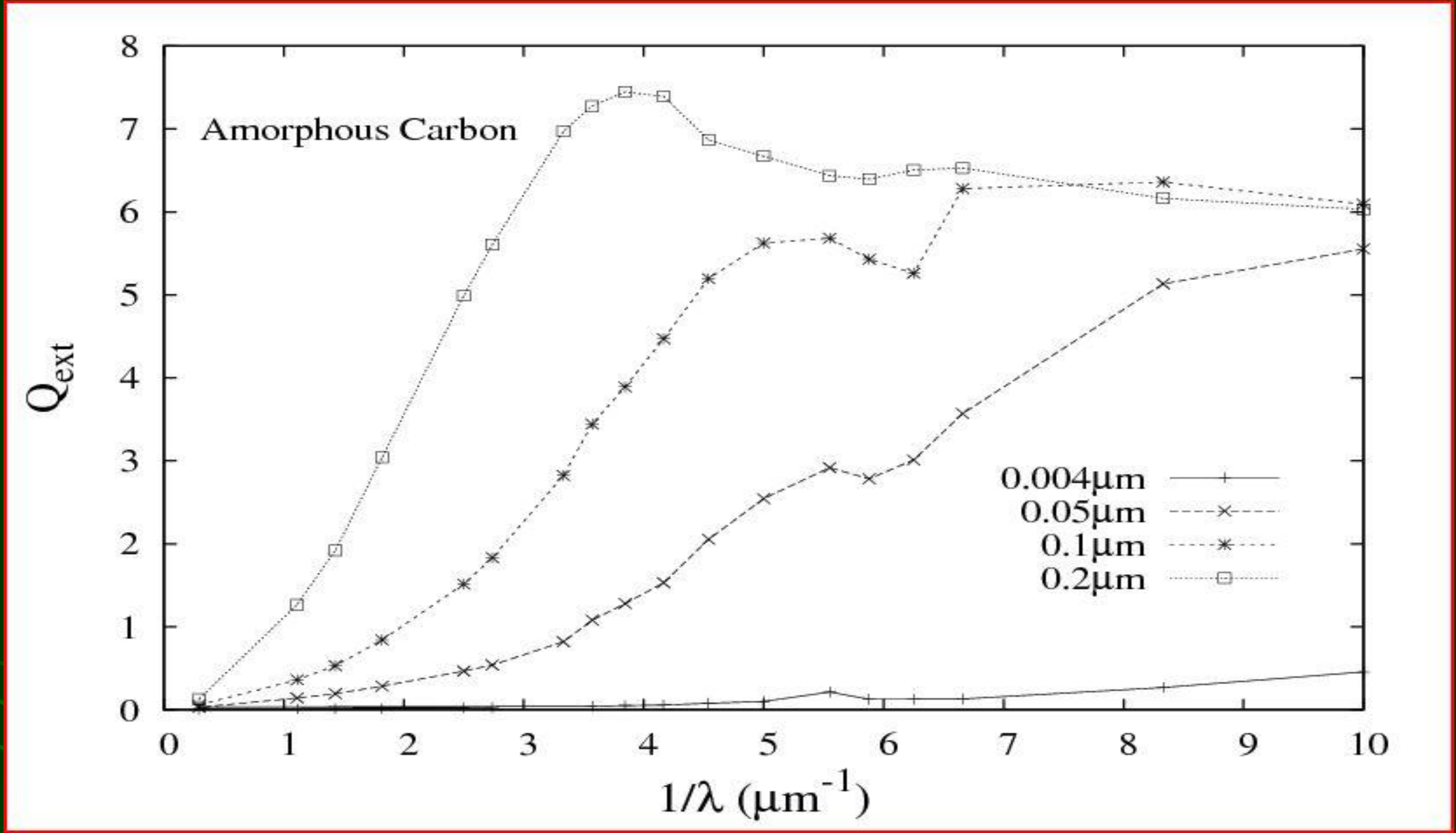


Fig.8: **Extinction efficiencies Q_{ext} versus 1/λ for randomly oriented amorphous carbon grains of sizes a = 0.004, 0.05, 0.1 and 0.2 μm in the wavelength range 3.4 to 0.11 μm.**

Best fit curve:

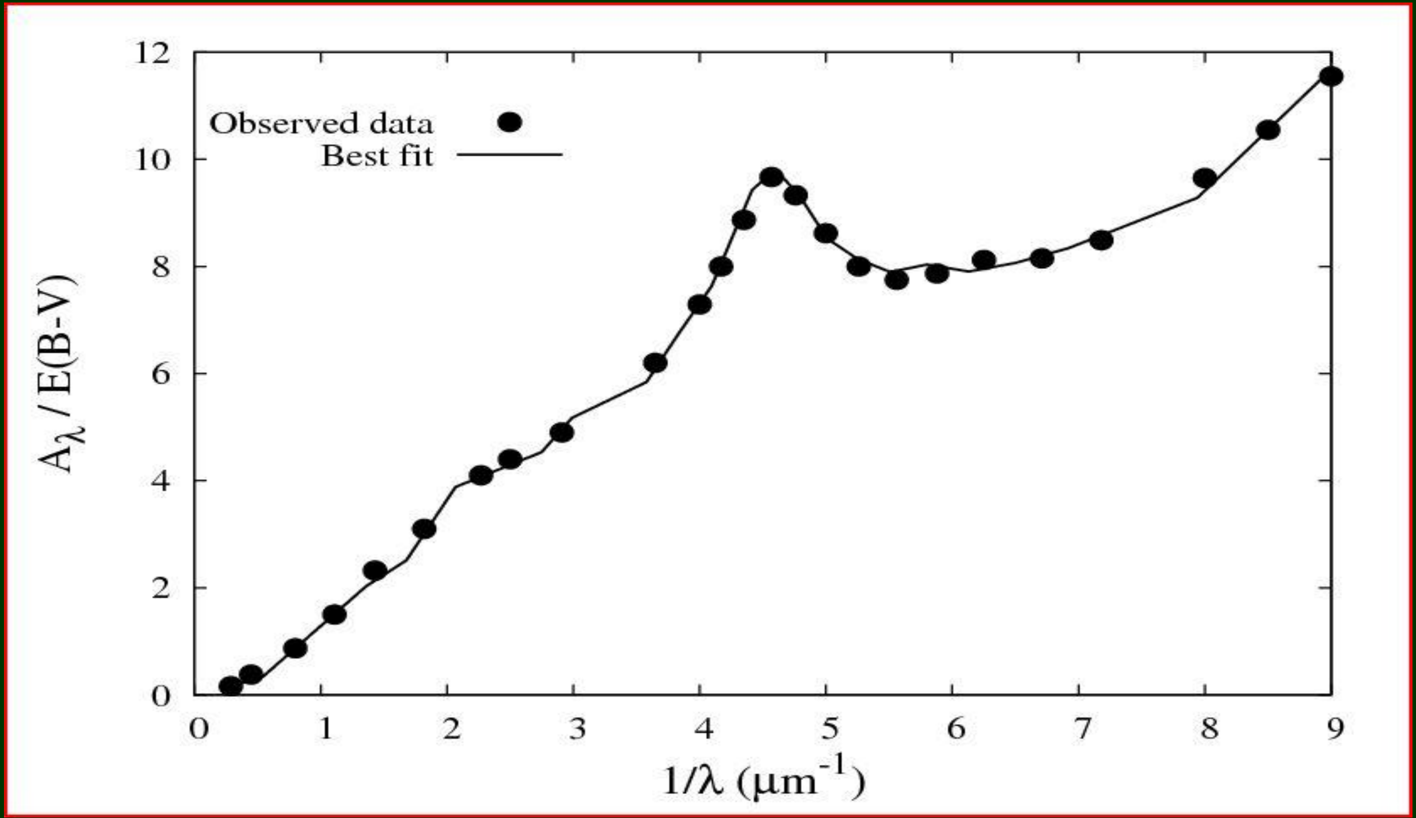


Fig. 9: The best fit average interstellar extinction curve for BCCA cluster in the wavelength region of 0.11 μm - 3.4 μm is obtained using a grain size distribution of 0.004 - 0.25 μm in steps of 0.004 μm. The best fit curve corresponds to a mixture of 45% silicate, 40% graphite and 15% amorphous carbon in the total mixture. The observed interstellar extinction data is taken from Savage & Mathis (1979), Whittet et al (2003).

Conclusion:

1. The size of the grains plays a major role in extinction properties of three different compositions taken in the present study. In order to study the extinction nature of interstellar dust, the size of the grains (a) is taken in the range 0.004 - 0.25μm, where well defined MRN size distribution $n(a) \sim a^{-3.5}$ is considered. We consider astronomical silicate, graphite and amorphous carbon aggregates to study the extinction efficiency of interstellar dust.

2. The well pronounced UV bump can be noticed for graphite grains at 2175Å. It is seen that for large size of the graphite grain, the UV-bump almost disappear. With the increase of size of the cluster, the peak shifts towards left and becomes broaden. However, silicate and amorphous carbon grains do not show such peak.

3. The best fit average extinction curve corresponds to a mixture of 45% silicate, 40% graphite and 15% amorphous carbon in the total mixture. The χ^2_{min} is found to be 0.11 which is lower than the value ($\chi^2_{min} = 0.1635$) obtained by Vaidya et al. (2007). Therefore it can be concluded that the aggregate dust model can be successfully able to explain the observed extinction properties of interstellar dust.

Thank you

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