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14. ABSTRACT
This work studied the relationship between light scattered by particles of any shape and the interior field of that particle. We discovered a new parameter, the “internal coupling parameter”, and we showed that it governs the role of the internal field to yield the external, scattered field and thereby is a unifying parameter to describe scattering by any particle shape. We also found another new parameter that can identify when the imaginary part of the refractive index makes a significant effect on the scattering. These theoretical advances helped us plan and interpret experimental studies. The experimental work demonstrated the importance of small angle scattering for large

15. SUBJECT TERMS
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19a. NAME OF RESPONSIBLE PERSON: Christopher Sorensen

19b. TELEPHONE NUMBER: 785-532-1626

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Report Title

Final Report: Q-space Scattering Power Laws and the Interior Fields of Particles

ABSTRACT

This work studied the relationship between light scattered by particles of any shape and the interior field of that particle. We discovered a new parameter, the “internal coupling parameter”, and we showed that it governs the role of the internal field to yield the external, scattered field and thereby is a unifying parameter to describe scattering by any particle shape. We also found another new parameter that can identify when the imaginary part of the refractive index makes a significant effect on the scattering. These theoretical advances helped us plan and interpret experimental studies. The experimental work demonstrated the importance of small angle scattering for large particles which has been ignored in previous experimental works by others. It discovered an empirical trend in the power law exponents seen with Q-space analysis with the internal coupling parameter. We also performed a theoretical study of light scattering by Gaussian random spheres, which mimic dusts, and found similar power law exponent trends with the internal coupling parameter. In summary, significant advances were made to understand the physical mechanism of light scattering and to quantitatively describe and parameterize scattering by any shape.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/11/2016	3.00	Yuli Wang, Amitabha Chakrabarti, Christopher M. Sorensen. A light-scattering study of the scattering matrix elements of Arizona Road Dust, Journal of Quantitative Spectroscopy and Radiative Transfer, (09 2015): 0. doi: 10.1016/j.jqsrt.2015.05.002
02/11/2016	1.00	William R. Heinson, Amitabha Chakrabarti, Christopher M. Sorensen. A new parameter to describe light scattering by an arbitrary sphere, Optics Communications, (12 2015): 0. doi: 10.1016/j.optcom.2015.08.067
02/11/2016	2.00	George Wang, Amitabha Chakrabarti, Christopher M. Sorensen. Effect of the imaginary part of the refractive index on light scattering by spheres, Journal of the Optical Society of America A, (06 2015): 0. doi: 10.1364/JOSAA.32.001231

TOTAL: **3**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Numerous but no records kept.

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
02/11/2016	5.00	BRENDAN M. HEFFERNAN, YULI W. HEINSON, JUSTIN B. MAUGHAN, AMITABHA CHAKRABARTI, CHRISTOPHER M. SORENSEN. Backscattering measurements of micron-sized spherical particles, Applied Optics (01 2016)
02/11/2016	6.00	Yuli W. Heinson, Justin B. Maughan, William R. Heinson, Amitabha Chakrabarti, Christopher M. Sorensen. Light Scattering Q-Space Analysis of Irregularly Shaped Particles, Journal of Geophysical Research - Atmospheres (09 2015)
02/11/2016	7.00	Amit Chakrabarti, Justin B. Maughan, Christopher M. Sorensen. Q-Space Analysis of Light Scattering by Gaussian Random Spheres, Journal of Quantitative Spectroscopy & Radiative Transfer (10 2015)
02/11/2016	4.00	Yuli W. Heinson, Amitabha Chakrabarti, Christopher M. Sorensen. A Light-Scattering Study of Al_2O_3 Abrasives of Various Grit Sizes, J. Quant. Spectrosc. Radiat. Transf. (02 2016)

TOTAL: **4**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
William R. Heinson	0.60	
Justin B. Maughan	0.40	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Christopher M. Sorensen	0.50	No
Amitabha Chakrabarti	0.50	
FTE Equivalent:	**1.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

William R. Heinson

Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment.

Technology Transfer

ARO Final Report
"Q-space Scattering Power Laws and the Interior Fields of Particles",
Agreement No. W911NF-14-1-0352. 7/7/2014 - 4/6/2015. Total rec'd $50,000.
C. M. Sorensen, PI

Statement of the Problem Studied

This work studied the relationship between light scattered by particles of any shape and the interior field of that particle. We discovered a new parameter, the "internal coupling parameter", and we showed that it governs the role of the internal field to yield the external, scattered field and thereby is a unifying parameter to describe scattering by any particle shape. We also found another new parameter that can identify when the imaginary part of the refractive index makes a significant effect on the scattering. These theoretical advances helped us plan and interpret experimental studies. The experimental work demonstrated the importance of small angle scattering for large particles which has been ignored in previous experimental works by others. It discovered an empirical trend in the power law exponents seen with Q-space analysis with the internal coupling parameter. We also performed a theoretical study of light scattering by Gaussian random spheres, which mimic dusts, and found similar power law exponent trends with the internal coupling parameter. In summary, significant advances were made to understand the physical mechanism of light scattering and to quantitatively describe and parameterize scattering by any shape.

Summary of the Most Important Results

This work proposed to investigate why light scattering angular intensity patterns for a wide variety of particle shapes display power law functionalities with the scattering wave vector q. We hypothesized that this occurs because the interior field is in some manner power law distributed in real space. To test this hypothesis numerical solutions of the Mie equations for spheres and the DDA algorithm for other shapes were used to calculate both the interior and exterior (scattered) fields. The strategy was to start at the diffraction limit where the phase shift parameter $\rho << 1$ and the interior field is the incident field, and its Fourier transform is directly related to the scattered field. Then we progressively increased ρ to watch the interior and scattered fields evolve. Significant progress was made for understanding the properties of the internal field and the consequences for the scattered field were made during the project period. Three papers were published [1-3], two are accepted for publication [4,5], and two are being written [6,7]. The hypothesis that the internal field was in some manner power law distributed was shown to be false. However, in our studies of the scattering as a function of the phase shift parameter we discovered a better parameter that replaces it. This is central to the goal of the project. We call the new parameter the "internal coupling parameter" and we showed that it governs the role of the internal field to yield the external, scattered field [1]. This parameter was inferred by the requirement that the scattering by a three dimensional sphere, which is described by the Mie formulation, must cross over to simple, two dimensional, Fraunhofer diffraction by a circular aperture in the limit of large and refractive spheres. Examination of this crossover was greatly facilitated by our concept and application of Q-space analysis. Q-space analysis studies the scattered intensity, I, not as a function of the scattering angle θ as is conventionally done, but rather as a function of the magnitude of the scattering wave vector q. Subsequently, we studied spherical particle scattering as described by the Mie equations for refractive indices that have both real and imaginary parts [2]. We found another new parameter that can identify when the imaginary part of the refractive index makes a significant effect on the scattering. We showed that a significant effect occurs when the interior field is confined to the forward facing “cap” of the particle with thickness equal to the well-known optical skin depth. For a given relative skin depth universal scattering occurs.

These theoretical advances helped us plan and interpret experimental studies to the extent that we acknowledged support from ARO in those papers. The experiments were performed with two new apparatuses that: 1) allowed for detection of scattered light simultaneously over a broad range of scattering angles including very small angles down to 0.3^0, [3, 6] and 2) detected light in the direct backscattering direction $\theta = 180^0 \pm 7^0$ [7]. With this Q-space perspective, a number of related results were discovered. The experimental work demonstrated the importance of small angle scattering for large particles which has been ignored in previous experimental works by others. It discovered an empirical trend in the power law exponents seen with Q-space analysis with the internal coupling parameter [4] that will need theoretical explanation. We also performed a theoretical study of light scattering by Gaussian random spheres, which mimic dusts, and found similar power law exponent trends with the internal coupling parameter [5]

Bibliography

1. W. R. Heinson, A. Chakrabarti and C. M. Sorensen, A New Parameter to Describe Light Scattering by an Arbitrary Sphere, Opt. Commun., 356, 612-615 (2015).

2. G. Wang, A. Chakrabarti and C. M. Sorensen, Effect of the Imaginary Part of the Refractive Index on Light Scattering by Spheres, J. Opt. Soc. Am. A32, 1231- 1235 (2015).

3. Y. Wang, A. Chakrabarti and C. M. Sorensen, A Light-Scattering Study of the Scattering Matrix Elements of Arizona Road Dust, Journal of Quantitative Spectroscopy & Radiative Transfer 163, 72-79 (2015).

4. Y. W. Heinson, J. Maughan, W. R. Heinson, A. Chakrabarti and C. M. Sorensen, Light Scattering Q-Space Analysis of Irregularly Shaped Particles, Journal of Geophysical Research – Atmospheres, accepted.

5. J. B. Maughan, A. Chakrabarti, C. M. Sorensen, Q-Space Analysis of Light Scattering by Gaussian Random Spheres, Journal of Quantitative Spectroscopy and Radiative Transfer, accepted.

6. Y. W. Heinson, A. Chakrabarti, C. M. Sorensen, A Light-Scattering Study of Irregularly Shaped Al_2O_3 Abrasives of Various Grit Sizes, Journal of Quantitative Spectroscopy & Radiative Transfer, submitted.

7. B. M. Heffernan, Y. W. Heinson, J. B. Maughan, A. Chakrabarti and C. M. Sorensen, Backscattering Measurements of Micron-sized Spherical Particles, Applied Optics, submitted.