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CMG Collaborative Research: Interactions of Phytoplankton with Dissipative Vortices

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Principal Investigator: Jumars, Peter A. **Award ID:** 0724744

Organization: University of Maine

Submitted By:

Jumars, Peter - Principal Investigator

Title:

CMG Collaborative Research: Interactions of Phytoplankton with Dissipative Vortices

Project Participants

Senior Personnel

Name: Jumars, Peter

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Karp-Boss, Lee

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Boss, Emmanuel

Worked for more than 160 Hours: No

Contribution to Project:

Emmanuel Boss actively engaged in our analysis and publication of estimates of characteristics of typical dissipative vortices.

Post-doc

Graduate Student

Name: Young, Ashley

Worked for more than 160 Hours: Yes

Contribution to Project:

Ashley has taken primary responsibility for measuring geometry and whole-chain mechanical properties of diatom chains (i.e., flexural stiffness). The procedure involved microscopic analysis of size and shape to produce a 3D CAD model and capture of the chain across the tip of a pipette with known inhalent flow velocity. Forces are calculated in COMSOL, and resultant flexure is measured microscopically. These data in turn are conveyed to Lisa Fauci and her postdoc Hoa V. Nguyen for implementation in their numerical models of chain behavior.

Undergraduate Student

Name: Bond, Samantha

Worked for more than 160 Hours: Yes

Contribution to Project:

With grant support, Samantha Bond has been running experiments with a fluorescent dye that indicates sites of most recent silica deposition. Her project is to study the localization of growing cells within diatom chains, testing the hypothesis that cells at the ends experience the greatest nutrient flux and hence divide most frequently.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Woods Hole Oceanographic Institution

Our discussions with John Trowbridge led to his joint authorship on one of our publications.

George Washington University

Magdalena M. Musielak did her Ph.D. and a postdoc with Lisa Fauci before she took a position at the George Washington University. We have been advising her on aspects of phytoplankton since her graduate work, and have just had accepted a manuscript from this work that was finished at the George Washington University.

Tulane University

Lisa Fauci and her postdoc, Hoa V. Nguyen are partners with us in this collaborative research. They are responsible for numerical modeling of the behavior of phytoplankton in dissipative vortices, whereas we at UMaine are involved in assessing characteristics of typical vortices, measuring shapes and mechanical properties of cells and chains and performing laboratory experiments to test the predictions from Fauci and Nguyen's models.

Weizmann Institute of Science

Lee Karp-Boss spent several months of the current project year making atomic force microscopy measurements of material properties of live diatom cells.

Other Collaborators or Contacts

Dr. Itay Rousso was Lee Karp-Boss' collaborator at the Weizmann Institute of Science.

Activities and Findings

Research and Education Activities:

We completed a simplified (2D) numerical analysis of nutrient uptake by phytoplankton chains in unsteady shear flow. We also completed an assessment of the characteristics of simple, model dissipative vortices. During 2010 and 2011, these model vortices formed the basis for choosing parameter values in Fauci and Nguyen?s embedding of model phytoplankton in a Burgers vortex, using immersed- boundary methods.

We made measurements of chain sizes and shapes and measurements of their bulk mechanical properties through engineering beam theory. During 2011 and 2012, this work was done by Ashley Young working with Pete Jumars and Lee Karp-Boss. It was complemented by nanoscale, atomic-force microscopic measurements of mechanical properties of diatoms by Lee Karp-Boss, who spent several months in two visits to the Weizmann Institute of Science in Israel. She conducted a series of nanoindentation experiments, using the chain-forming diatom Lithodesmium undulatum as a target species. Our goal in this set of experiments was to examine the microscale spatial variability of elastic properties (Young?s modulus) of the cell wall (frustule) and the siliceous structure that connects cells to form chains (marginal ridge). Karp-Boss is preparing that work for submission.

We developed mechanical models that relate local material properties, through engineering models, to bulk mechanical properties like flexural stiffness of the whole 'beam' that is a diatom chain suspended across a pipette tip. During the last two years we also added measurement of fluorescence as an indication of silica deposition (LeBlanc and Hutchins 2005) to determine whether cells at specific locations in chains are dividing more frequently than in other locations. We have also done culture experiments to measure effects of nutrient starvation on mechanical properties. Undergraduate Samantha Bond extended these experiments to look at nutrient effects on chain length.

Jumars used COMSOL, a finite element modeling environment, to produce estimates of flow velocity near the capillary tip used in Young?s experiments. They are related to classic pipe-inlet problems for developing flows because the standard assumption of uniform inflow velocity did not apply.

We have also worked closely with Nguyen and Fauci to examine effects of numbers, lengths and orientations of spines on motion of cells in shear flows as a next step in assessing form and function. To maintain some realism, some of our models bore close resemblance in form to Thalassiosira punctigera.

Jumars extended the COMSOL models used for estimating capillary velocities to the bulk fluid outside the capillary because this type of suction flow is widely used to elicit zooplankton escape responses and to interpret flows produced by active benthic suspension feeders. The analogy is to flows produced by predators, but the modeling suggested that the parameterizations used in these previous studies are inaccurate. Jumars ran simulations for two geometries, a capillary drawing water from the middle of a large tank and a drain exiting the middle of the bottom of a large tank, covering the full range of laminar pipe Reynolds numbers from 0.01 to 2,000.

Jumars also has continued modeling other microfluidic environments that could also be used to test predictions of relative motions seen in Fauci and Nguyen?s simulations. Pressure forces on a particle are unbalanced if it is within a small vortex, so we are beginning to explore microfluidic environments wherein those unbalanced forces are exaggerated as a means besides Jeffery orbits wherein differential motion of fluid and particles.

In the last few months of the grant we used a custom-made imaging device (volumetric particle imager, or VoPI, in collaboration with Evan Variano UC Berkeley) to collect information on 3D trajectories of diatoms in a turbulent flow, in order to asses effects of turbulence on sinking velocities of diatoms. Images were collected for two species (a chain former and a solitary one) and are currently being processed.

Refence cited:

LeBlanc, K, and D.A. Hutchins. 2005. New applications of a biogenic silica deposition fluorophore in the study of oceanic diatoms. Limnol. Oceanogr.: Methods 3: 462-476.

Findings:

The 2D model (Musielak et al. 2009) suggests that, when nutrients are regenerated as point sources distributed randomly in space, more rigid chains achieve higher nutrient uptake by spanning a larger space.

Theoretical dissipation spectra and direct numerical simulation indicate that typical dissipative vortices with radii of 7 to 8 times the Kolmogorov scale, peak azimuthal speeds of order 1 cm s^-1 and lifetimes of order 10 s as a minimum (and much longer for moderate pelagic turbulence intensities) deserve new attention in studies of biological effects of turbulence. The Burgers model appears to be a good approximation to vortices seen most often in direct numerical simulations (Jumars et al. 2009).

Bulk estimates of flexural stiffness from the pipette method now cover four orders of magnitude, with large differences among species (Young 2011; Young et al. 2012). Initial results of our atomic force measurements showed high spatial variability in the Young?s modulus, with values ranging from 300-9000 kPa (where lower values represent a ?softer? region and higher values represent a more rigid region). These values are much lower than values reported previously in the literature for clean frustules (~ 1-10 GPa), but of the same order as values obtained by the only other study that examined living cells. Our data suggest that older portions of the frustule (less recently deposited) show greater rigidity (Karp-Boss, in preparation). These studies have also shown that newly laid down silica is softer to nanoindentation than older silica, revealing an important source of the high variance observed.

Our most recent bulk flexural stiffness experiments show high sensitivity to nutrient ratios. Silica-starved cells show surprisingly little change in Young's modulus (rigidity of the whole 'beam') but are very fragile, i.e., break after bending very little (Young et al. 2012). These findings have implications for mechanical costs and net benefits of grazing. The honors thesis of undergraduate Samantha Bond showed that proportions of long chains decreased under nutrient starvation, consistent with Young et al.?s results. Ms. Bond presented her results at the annual University of Maine undergraduate research symposium and received the best student poster award.

We have helped Fauci and Nguyen (Tulane) produce integrated models of chain mechanics that are consistent in mechanical behavior in the immersed boundary method, in bulk flexural stiffness, and in local resistance to deformation. Consistency is essential, as the immersed boundary method's results prove sensitive to flexural stiffness when the flow geometry is complex, such as in or near a vortex. Realistically modeled phytoplankton, in turn, fail to follow the same trajectories as would a parcel of water starting at the same point, with consequences for nutrient uptake, predator encounter and coagulation.

Spine numbers, lengths and orientations all prove to have substantial effects, but the bulk of the variation in rotation frequency in shear can be predicted from the early work of Jeffery by using results for the rigid spheroid that minimally inscribes the cell and its spines. Spines thus can achieve effective shape change that greatly alters rotational frequency without the need to change underlying body shape and with substantially less material than would be needed to fill the inscribing spheroid (Nguyen et al. 2011).

Our COMSOL models, as we had originally proposed, are illuminating laboratory flow environments. Suction flows into capillaries have been used widely by researchers to elicit escape responses by zooplankton. These flows have generally been modeled as spherical, point sinks, implying that velocity falls off as the square of the distance from the pipette tip. The models used to estimate flow velocity just inside the pipette opening for our flexural stiffness work show quite clearly that the point-sink model is quite far from that fall-off pattern (faster in some directions and slower in others) and that flow geometry varies with capillary Reynolds number (Jumars, revision in review). Our new models of suction flow into a capillary should make these flows even more useful for diverse experimental applications to plankton. They clearly show that the assumption of uniform inflow velocity nearly universally used in the past cannot apply to common flow settings for Reynolds numbers that cover the entire laminar range (< 2000).

Jumars, P.A., E. Boss, J.H. Trowbridge and L. Karp-Boss. 2009. Turbulence-plankton interactions: A new cartoon. Marine Ecology 30: 133-150.

Musielak, M.M., L. Karp-Boss, P.A. Jumars and L.J. Fauci. 2009. Nutrient transport and acquisition by diatom chains in a moving fluid. J. Fluid Mech. 638: 401-421.

Nguyen, H. L. Karp-Boss, P.A. Jumars and L.J. Fauci. 2011. Hydrodynamic effects of spines: a different spin. Limnology and Oceanography: Fluids and Environments. 1: 110-119.

Young, A.M., L. Karp-Boss, P.A.Jumars and E.N.Landis. 2012. Quantifying diatom aspirations: Mechanical properties of chain-forming species. Limnol. Oceanogr. 57: in press.

Jumars, P.A. Boundary-trapped, inhalant siphon and drain flows: Pipe entry revisited numerically. Limnol. Oceanogr.: Fluids Envmt., in second review.

Training and Development:

Ashley Young, while learning electron microscopy and completing a classic biological oceanography curriculum, developed methods for measuring bulk mechanical properties of fully wetted diatom chains. Jumars used information that he learned about small-scale vortices in presenting fluid dynamic phenomena to an intensively hands-on, undergraduate class (SMS 204) that applies principles of physics to oceanographic phenomena and used that information also in high school outreach in early June 2009. He also incorporated it in his hands-on biological fluid dynamics course for undergraduates taught in fall 2010 (SMS 481).

Samantha Bond, holder of a NOAA Ernest F. Hollings fellowship learned phytoplankton culture methods and experimental techniques. She used the work for her honor's thesis. The poster she presented won the best poster award at UMaine's annual undergraduate research symposium. She is very likely to follow through to publication.

We have introduced Philip Benoit, a student at Orono High School, to laboratory-based research and anticipate that his interest in STEM fields will continue.

Outreach Activities:

We have developed further some concept maps for relating to broader audiences the importance of marine turbulence at the scale of individual plankters and plan to present those relationships through web visuals to be completed in the final year of the grant. Jumars successfully tested the approach in September 2010 at an evening lecture to retired persons who organized a science-oriented evening lecture series.

Our major outreach effort will occur in December 2012 (after the end of the grant) in the form of three webinars to be produced with assistance from COSEE-OS. They will be broadcast live and then archived at http://cosee.umaine.edu/programs/webinars/. This series of webinars has seen very high use from secondary school educators. We are producing them in collaboration with Don Webster and Jeannette Yen of Georgia Tech. The series will begin with an introduction to turbulence, move to biological effects of turbulence and finish with projections of effects that climate change will exert on such effects.

Journal Publications

Jumars, P.A., Boss, E., Trowbridge, J.H., and Karp-Boss, L., "Turbulence-plankton interactions: A new cartoon", Marine Ecology, p. 13, vol. 30, (2009). Published, doi:10.1111/j.1439-0485.2009.00288.x

Musielak, M.M., L. Karp-Boss, P.A. Jumars and L.J. Fauci, "Nutrient transport and acquisition by diatom chains in a moving fluid", Journal of Fluid Mechanics, p. 401-42, vol. 638, (2009). Published, 10.1017/S0022112009991108

Nguyen, H, L. Karp-Boss, P. A. Jumars, and L. Fauci, "Hydrodynamic effects of spines: A different spin", Limnology & Oceanography: Fluids & Environments, p. 110-119, vol. 1, (2011). Published, 10.1215/21573698-1303444

Young, A.M., L. Karp-Boss, P.A. Jumars and E.N. Landis, "Quantifying diatom aspirations: mechanical properties of chain-forming species", Limnology and Oceanography, p. , vol. 57, (2012). Accepted, Jumars, P.A., "Boundary-trapped, inhalant siphon and drain flows: pipe entry revisited numerically", Limnol. Oceanogr.: Fluids Envmts., p. , vol. , (2012). Submitted,

Books or Other One-time Publications

Young, Ashley M., "QUANTIFYING DIATOM ASPIRATIONS: MECHANICAL PROPERTIES OF CHAIN-FORMING SPECIES", (2011). Thesis, Archived University of Maine (Fogler) Library <http://www.library.umaine.edu/t>
Bibliography: M.S. Thesis, University of Maine. 103 pp.
<http://www.library.umaine.edu/theses/pdf/restricted/YoungA2011.pdf>

Web/Internet Site

URL(s):

http://www.umaine.edu/marine/people/sites/pjumars/

Description:

This site briefly describes the work and serves reprints and preprints.

Other Specific Products

Contributions

Contributions within Discipline:

The modeling of Burgers vortices in Jumars et al. (2009) is leading to more sophisticated testing of turbulence effects on plankton than has been possible with prior approaches in simple Couette flow. We anticipate that it will reveal mechanical and behavioral means for herbivores to reach and remain in areas of high particulate food concentration and will give a better idea of the frequency of tumbling in diatoms caused by unsteady small-scale fluid dynamics. Existing studies already show that nutrient exchange is accelerated in such tumbling events.

The results of Musielak et al. (2009) provide a mechanistic link between mechanical properties of chains and nutrient gains by pointing out greater flexural stiffness can lead to enhanced nutrient uptake. Nguyen et al. (2011), in turn, provide a novel interpretation of the role of spines in enhancing tumbling of cells (and in turn enhancing relative motion of fluid and the cell and hence nutrient supply to the cell). They also provide a very simple approximation to the tumbling expected by approximating the cell, inclusive of its spines, with the smallest spheroid capable of inscribing the cell and its spines.

The measurements made by Young (2011 and 2012) are the first measurements made of the bulk mechanical properties of diatom chains. They open the door to modeling of diatom chain motions in natural flows through immersed-boundary methods that require specifications of the physical properties of both the fluid and the particle moving in it. This is a vital contribution to knowledge in the area of biological-physical coupling.

The results of Jumars (in review) improve the quantification of siphon flows that form the basis of many biological oceanographic experiments that create flow fields in order to elicit escape reactions of zooplankton, stimulate bioluminescence and measure flexural stiffness of fibers and diatom chains. The results, that cover the full range of steady, laminar flow behavior, show low, transitional and high Reynolds number states for siphon flows and flows into drain pipes. The siphon findings for low and intermediate Reynolds numbers show two alternative stable states that have strong implications for mechanical costs of suspension feeding and for the ability of suspension feeders to resolve spatial dimensions through chemosensing of components in the inhalant stream.

Contributions to Other Disciplines:

Our collaboration with Lisa Fauci and Hoa Nguyen of Tulane is 'stretching' the applications of immersed boundary methods by helping to incorporate realistic solid mechanical properties for particles affected by the local flow. It may enable novel flow sorting methods based on particle shapes or mechanical properties.

Jumars (in review) findings for pipe entry reconcile the departure of experimental results from predictions, especially for pipe Reynolds numbers below 200. They show that these two common entrance geometries (a pipe far from other boundaries and a drain flush with the bottom of a tank) at Reynolds numbers less than 200 deviate substantially from the standard assumption of uniform entrance velocity, reducing entrance length by more than half for Reynolds numbers less than 5. At Reynolds numbers between 200 and 2000, on the other hand, radial inrush of fluid also alters dynamics substantially from the assumption of uniform, axis-parallel entrance velocity, in this case through substantial radial inrush of fluid and a resultant adverse pressure gradient at the inside lip of the pipe or drain. The results also have implications for sampling of fluids.

Contributions to Human Resource Development:

Our project covers the spectrum from senior researchers, through a postdoc, to a graduate student, to an undergraduate student to a high school student in an endeavor to keep the STEM pipeline going. We are gratified that our M.S. student, Ashley Young, is preparing for a career in science teaching at the secondary school level.

Contributions to Resources for Research and Education:

Jumars incorporates these results into his teaching of a hands-on class for undergraduates in 'Design of Marine Organisms,' showing how their form and function is influenced by momentum, mass and information transfer through aquatic media. Successful approaches to conveying complex biological-physical coupling are being used in preparing a draft book that emphasizes low Reynolds numbers for use in teaching as a companion to Vogel's 'Life in Moving Fluids.'

We anticipate that the webinars in preparation for COSEE-OS will be widely used by high school teachers and college teachers.

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Any Product

Contributions: To Any Beyond Science and Engineering

Any Conference