Astrobiological and Geological Implications of Convective Transport in Icy Outer Planet Satellites

Final Progress Report

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PROGRESS STATEMENT:

The oceans of large icy outer planet satellites are prime targets in the search for extraterrestrial life in our solar system. The goal of our project has been to develop models of ice convection in order to understand convection as an astrobiologically relevant transport mechanism within icy satellites, especially Europa. These models provide valuable constraints on modes of surface deformation and thus the implications of satellite surface geology for astrobiology, and for planetary protection.

Over the term of this project, significant progress has been made in three areas: (1) the initiation of convection in large icy satellites, which we find probably requires tidal heating; (2) the relationship of surface features on Europa to internal ice convection, including the likely role of low-melting-temperature impurities; and (3) the effectiveness of convection as an agent of icy satellite surface-ocean material exchange, which seems most plausible if tidal heating, compositional buoyancy, and solid-state convection work in combination.

Description of associated publications follows, and includes: 3 published papers (including contributions to 1 review chapter), 1 manuscript *in revision*, 1 manuscript *in preparation* (currently being completed under separate funding), and 1 published popular article. A myriad of conference abstracts have also been published, and only those from the past year are listed below. Over the course of this work, salary and travel support has been provided to Principal Investigator R. Pappalardo and to University of Colorado graduate student Amy Barr.

PUBLISHED PAPERS:

Barr, A. C., S. Zhong, and R. T. Pappalardo. Convective instability in ice I with non-Newtonian rheology: Application to the Galilean satellites. ***J. Geophys. Res.*, *109*, E12008, doi:10.1029/2004JE002296, 2004.**

At the temperatures and stresses associated with the onset of convection in an ice I shell of the Galilean satellites, ice behaves as a non-Newtonian fluid with a viscosity that depends on both temperature and strain rate. The convective stability of a non-Newtonian ice shell can be judged by comparing the Rayleigh number of the shell to a critical value. Previous studies suggest that the critical Rayleigh number for a non-Newtonian fluid depends on the initial conditions in the fluid layer, in addition to the thermal, rheological, and physical properties of the fluid. We seek to extend the existing definition of the critical Rayleigh number for a non-Newtonian, basally heated fluid by quantifying the conditions required to initiate convection in an ice I layer initially in conductive equilibrium. We find that the critical Rayleigh number for the onset of convection in ice I varies as a power (-0.6 to -0.5) of the amplitude of the initial temperature perturbation issued to the layer, when the amplitude of perturbation is less than the rheological temperature scale. For larger-amplitude perturbations, the critical Rayleigh number achieves a constant value.

We characterize the critical Rayleigh number as a function of surface temperature of the satellite, melting temperature of ice, and rheological parameters so that our results may be extrapolated for use with other rheologies and for a generic large icy satellite. The values of critical Rayleigh number imply that triggering convection from a conductive equilibrium in a pure ice shell less than 100 km thick in Europa, Ganymede, or Callisto requires a large, localized temperature perturbation of a few kelvins to tens of kelvins to soften the ice and therefore may require tidal dissipation in the ice shell.

Pappalardo, R. T. and A. C. Barr, Origin of domes on Europa: The role of thermally induced compositional buoyancy, *Geophys. Res. Lett.*, *31*, L01701, doi:10.1029/2003GL019202, 2004.

The surface of Jupiter's moon Europa is peppered by topographic domes, interpreted as sites of intrusion and extrusion. Diapirism is consistent with dome morphology, but thermal buoyancy alone cannot produce sufficient driving pressures to create the observed dome elevations. Instead, diapirs may initiate by thermal convection that induces compositional segregation. Exclusion of impurities from warm upwellings allows sufficient buoyancy for icy plumes to create the observed surface topography, provided the ice shell has a small effective elastic thickness (0.2 to 0.5 km) and contains low-eutectic point impurities at the few percent level. This model suggests that the ice shell may be depleted in impurities over time.

Greeley, R., C. Chyba, J. W. Head, T. McCord, W. B. McKinnon, and R. T. Pappalardo, Geology of Europa, in *Jupiter: The Planet, Satellites & Magnetosphere* (F. Bagenal et al., eds.), pp. 329-362, 2004.

Europa is a rocky object of radius 1565 km (slightly smaller than Earth's moon) and has an outer shell of water composition estimated to be of order 100 km thick, the surface of which is frozen. The total volume of water is about 3×10^9 km^3, or twice the amount of water on Earth. Moreover, like its neighbor Io, Europa experiences internal heating generated from tidal flexing during its eccentric orbit around Jupiter. This raises the possibility that some of the water beneath the icy crust is liquid. The proportion of rock to ice, the generation of internal heat, and the possibility of liquid water make Europa unique in the Solar System. In this chapter, we outline the sources of data available for Europa (with a focus on the Galileo mission), review previous and on-going research on its surface geology, discuss the astrobiological potential of Europa, and consider plans for future exploration.

PAPER IN REVISION:

Barr, A. C. and R. T. Pappalardo. Onset of convection in ice I with composite Newtonian and non-Newtonian rheology: Application to the icy Galilean satellites. *J. Geophys. Res.*, in revision.

Ice I exhibits a complex rheology at temperature and pressure conditions appropriate for the interiors of the ice I shells of Europa, Ganymede, and Callisto. We use numerical methods and existing parameterizations of the critical Rayleigh number to determine the conditions required to trigger convection in an ice I shell with the stress-, temperature- and grain size- dependent rheology measured in laboratory experiments by *Goldsby and Kohlstedt* [2001]. The critical Rayleigh number depends on the ice grain size and the amplitude and wavelength of temperature perturbation issued to an initially conductive ice I shell. If the shells have an assumed uniform grain size less than 0.4 mm, deformation during initial plume growth is accommodated by Newtonian volume diffusion. If the ice grain size is between 0.4 mm and 3 cm, deformation during plume growth is accommodated by weakly non-Newtonian grain boundary sliding, where the critical ice shell thickness for convection depends on the amplitude of temperature perturbation to the _0.5 power. If the ice grain size exceeds 2 cm, convection can not occur in the ice I shells of the Galilean satellites regardless of the amplitude or wavelength of temperature perturbation. If the grain size in a convecting ice I shell evolves to effective values greater than 2 cm, convection will cease. If the ice shell has a grain size large enough to permit flow by dislocation creep, the ice is too stiff to permit convection, even in the thickest possible ice I shell. Consideration of the composite rheology implies that estimates of the grain size in the satellites and knowledge of their initial thermal states are required when judging the convective instability of their ice I shells.

PAPER IN PREPARATION:

Barr, A. C. and R. T. Pappalardo. Convection in icy satellites: Implications for habitability and planetary protection. In preparation for *Astrobiology*.
Solid-state convection and endogenic resurfacing in the outer ice shells of the icy Galilean satellites (especially Europa) may contribute to the habitability of their internal oceans and to the detectability of any biospheres by spacecraft. If convection occurs in an ice I layer, fluid motions are confined beneath a thick stagnant lid of cold, immobile ice that is too stiff to participate in convection. The thickness of the stagnant lid varies from 30 to 50% of the total thickness of the ice shell, depending on the grain size of ice. Upward convective motions deliver $\sim 10^9$ to 10^{13} kg yr^{-1} of ice to the base of the stagnant lid, where resurfacing events driven by compositional or tidal effects (such as the formation of domes or ridges on Europa, or formation of grooved terrain on Ganymede) may deliver materials from the stagnant lid onto the surface. Conversely, downward convective motions deliver the same mass of ice from the base of the stagnant lid to the bottom of the satellites' ice shells. Materials from the satellites' surfaces may be delivered to their oceans by downward convective motions if material from the surface can reach the base of the stagnant lid during resurfacing events. Triggering convection from an initially conductive ice shell requires modest amplitude (a few to tens of kelvins) temperature anomalies to soften the ice to permit convection, which may require tidal heating. Therefore, tidal heating, compositional buoyancy, and solid-state convection in combination may be required to permit mass transport between the surfaces and oceans of icy satellites. Callisto and probably Ganymede have thick stagnant lids with geologically inactive surfaces today, so forward contamination of their surfaces is not a significant issue. Active convection and breaching of the stagnant lid is a possibility on Europa today, so is of relevance to planetary protection policy.

POPULAR ARTICLE:

Pappalardo, R. T. Jupiter's water worlds. *Astronomy, 32(1)*, 34-41, 2004.
When the twin Voyager spacecraft cruised past Jupiter in 1979, they did more than rewrite the textbooks on the giant planet. Their cameras also unveiled the astounding diversity of the four planet-size moons of ice and stone known as the Galilean satellites. The Voyagers revealed the cratered countenance of Callisto, the valleys and ridges of Ganymede, the cracked face of Europa, and the spewing volcanoes of Io. But it would take a spacecraft named for Italian scientist Galileo, who discovered the moons in 1610, to reveal the true complexity of these worlds and to begin to divulge their interior secrets. Incredibly, the Galileo data strongly suggest that Jupiter's three large icy moons (all but rocky Io) hide interior oceans.

RECENT CONFERENCE ABSTRACTS:

Barr, A. C., and R. T. Pappalardo. Convection in the icy satellites: Implications for astrobiology. *Astrobiology, 2*, 304-305, 2005.

Barr, A. C., and R. T. Pappalardo. Convection in ice I with composite Newtonian/non-Newtonian rheology: Application to the icy Galilean satellites. *Proc. Lunar Planet Sci. Conf. XXXVI.* Abstract #2146, 2005.

Barr, A. C., and R. T. Pappalardo. Onset of convection in ice I with a composite Newtonian/non-Newtonian rheology. *Bull Amer. Astron. Soc., 36 (4)*, abstract #9.07, 2004.