A Workshop on Multi-Messenger Tomography of Earth

Snowbird, Utah

July 30-31, 2022

Welcome Address

We are organizing an in-person mini-workshop on "Multi-messenger Tomography of Earth (MMTE 2022)" during July 30th to 31st at The Cliff Lodge at Snowbird, Salt Lake City, Utah, USA.
The idea is to bring together leading experts from the neutrino and geoscience communities to discuss in depth the present status of the field and its future developments. The main aim of this workshop is to explore the role of oscillation and absorption neutrinos towards the tomography of Earth - complementary to the seismic studies and gravitational measurements - paving the way for multi-messenger tomography of Earth.
The huge amount of high-quality atmospheric neutrino data that we expect to collect in the next 10 to 15 years using IceCube/IceCube-Gen2, DeepCore and its upgrade, ORCA and ARCA, Hyper-K, DUNE, and INO-ICAL with its CID capability, are going to play an important role along this direction.

Contents

MMTE 2022 Abstract Submissions

30 July
9:30am
R: Wasatch A/B

Atmospheric Neutrinos for Non-Specialists

Edward Kearns, Boston University
email: kearns@bu.edu

The aim of this talk is to set the stage for the neutrino tomography workshop and to provide basic information about the properties of atmospheric neutrinos. I will present a pedagogical overview on atmospheric neutrinos, their history, and briefly review their current use in the study of neutrino oscillation.

The Internal Structure of the Earth

30 July
10:15am
R: Wasatch A/B

Bill McDonough, University of Maryland
email: mcdonoug@umd.edu

For a century the earth's interior (core (liquid)-mantle-crust) has been recognized and since we have identified a solid inner core and now many new structures that are "anchored" on the core-mantle-boundary (CMB). Moreover, we have successfully imaged subducting oceanic plates penetrating the upper mantle and many entering the lower mantle (>660 km). Over the last two decades, geoneutrino flux measurements are quantifying earth's radiogenic power, giving us the first global determination of bulk composition. More recently the detection of atmospheric and cosmological neutrinos that have traversed the earth are offering a new opportunity to measure other attributes of the earth's interior, mainly its density structure and hydrogen content. The age, origin, nature, and dynamic evolution of these structures will be discussed.

---

30 July
11:30am
R: Wasatch A/B

Imaging the Earth's Interior using Seismic Waves

Vedran Lekic, University of Maryland, College Park
email: ved@umd.edu

Earthquakes, ocean waves, and human activity produce seismic waves that travel through the Earth, carrying with them information about variations in elastic properties and density. Since pioneering efforts in the late 1970s, global seismic tomography has revealed structures in our planet's deep interior at increasingly greater detail. Here, I present recent progress in determining Earth's elastic and density structure, and discuss key structures at various scales. Finally, I review challenges and limitations facing seismologists in their efforts to obtain more precise images of the interior.

Present status and future prospects of geoneutrinos towards Earth tomography

30 July
12:15pm
R: Wasatch A/B

Andrea Serafini, University of Ferrara INFN
email: serafini@fe.infn.it

No abstract submitted.

---

30 July
2:30pm
R: Wasatch A/B

The first neutrino absorption Earth tomography

Andrea Donini, Boston University
email: email@email.com

No abstract submitted.

Measuring density of Earth's core using high-energy neutrinos observed by IceCube

30 July
3:15pm
R: Wasatch A/B

Kotoyo Hoshina, University of Wisconsin Madison
email: hoshina@icecube.wisc.edu

The world largest neutrino observatory IceCube, located at the South Pole, is collecting high-energy neutrino events for over 10 years, and has observed a diffuse cosmic neutrino flux since 2013. While the main aim is searching for extra-terrestrial neutrinos, the collected data contains a large sample of atmospheric neutrino interactions as background events. Using our understanding of the atmospheric neutrino flux and detector systematics of IceCube, these events can be utilised to probe for the density structure of the Earth's interior. In this talk we discuss the analysis method and expected performanceusing the IceCube muon neutrino sample collected from 2010 to 2020.

30 July
4:10pm
R: Wasatch A/B

Chemical composition and hydrogen content inside Earth

Kei Hirose, The University of Tokyo
email: kei@eps.s.u-tokyo.ac.jp

Hydrogen is a strongly siderophile (iron-loving) element under typical conditions of Earth's core formation (40–50 GPa, 3500 K); its metal/silicate partition coefficient *D*(H) (metal/silicate) = 50 by weight (Tagawa et al., 2021 Nat. Commun.). Considering the amount of H2O in the mantle and oceans, such high *D*(H) (metal/silicate) suggests 0.3–0.6 wt% H in the core, which accounts for 30–60 % of the outer core density deficit and velocity excess compared to pure iron. The 0.3–0.6 wt% H in the outer core is compatible with seismological observations of its density and velocity; indeed, ab initio calculations showed these observations are explained with 1.0 wt% H as a single light element (Umemoto and Hirose, 2020 EPSL). The solid-Fe/liquid-alloy partition coefficient of hydrogen *D*(H) (solid-Fe/liquid) was recently determined to be 0.7 by weight in the Fe-Si-H system at 50 GPa (Hikosaka et al., 2022 SciRep). If it can be applied to inner core conditions (¿330 GPa), the solid core may include 0.2–0.4 wt% H. It agrees with recent theoretical calculations of a possible range of the inner core composition that explains the observed density, compressional and shear velocities (Wang et al., 2021 EPSL). Note that the presence of carbon and/or hydrogen is important to explain the low shear/compressional velocity ratio characteristic of the inner core (He et al., 2022 Nature). In addition, Fe-FeH has recently been found to be an eutectic system (Tagawa et al., 2022 JGR), and the melting (liquidus) temperature of Fe-H alloys is low, in particular when 0.3–0.6 wt% H is included. It suggests low core temperatures, consistent with the fact that the base of the mantle is not globally molten. The 0.3–0.6 wt% H in the core is thus favored, but the present estimate depends largely on the mantle water abundance and the Earth's accretion process. Neutrino observations will be very helpful if they provide additional constraints on hydrogen concentration in the deep interior.

A coupled core-mantle evolution

30 July
4:55pm
R: Wasatch A/B

Takashi Nakagawa

email: takashi.geodynamics@gmail.com

I would give a brief review on the topic concerning the core-mantle co-evolution in terms of thermal and chemical evolution of Earth's core constrained from the mantle dynamics of Earth. In this talk, several controversial aspects in current understandings of thermal and chemical evolution of the Earth's core will be introduced: 1. The age of inner core (greatly uncertain in between 1 Ga to 3 Ga) and potential energy source for geodynamo operating over 4 billion years, 2. Emergence of stably stratified region at the uppermost outer core and its origin (thermal or chemical) and 3. possibility on the radiogenic heat source in Earth's core.

Oscillation tomography of the Earth with solar neutrinos and future experiments

30 July
5:20pm
R: Wasatch A/B

Pouya Bakhti[1] and **Alexei Yu. Smirnov**[2]

[1]JBNU; [2]Max-Planck Institute for Nuclear Physics

email: [1]pouya$_b akhti@jbnu.ac.kr$[2]smirnov@mpi-hd.mpg.de

We study in details the Earth matter effects on the boron neutrinos from the Sun using recently developed 3D models of the Earth. The models have a number of new features of the density profiles, in particular, a substantial deviation from spherical symmetry. In this connection, we further elaborate on relevant aspects of oscillations (ϵ^2 corrections, adiabaticity violation, entanglement, *etc.*) and the attenuation effect. The night excesses of the $\nu e-$ and $\nu N-$ events and the Day-Night asymmetries, A_{ND}, are presented in terms of the matter potential and the generalized energy resolution functions. The energy dependences of the cross-section and the flux improve the resolution, and consequently, sensitivity to remote structures of the profiles. The nadir angle (η) dependences of A_{ND} are computed for future detectors DUNE, THEIA, Hyper-Kamiokande, and MICA at the South pole. Perspectives of the oscillation tomography of the Earth with the boron neutrinos are discussed. Next-generation detectors will establish the integrated day-night asymmetry with high confidence level. They can give some indications of the $\eta-$ dependence of the effect, but will discriminate among different models at most at the $(1-2)\sigma$ level. For high-level discrimination, the MICA-scale experiments are needed. MICA can detect the ice-soil borders and perform unique tomography of Antarctica.

Landscape of Neutrino Physics

Francis Halzen, University of Wisconsin
email: francis.halzen@icecube.wisc.edu

31 July
9:00am
R: Wasatch A/B

In the last decade IceCube has opened a new window on the Universe using neutrinos as astronomical messengers. The instrument detects more than 100,000 neutrinos per year in the GeV to 10,000 TeV energy range. IceCube and similar detectors now under construction or at the concept stage, will perform neutrino physics with high statistics samples of atmospheric neutrinos and with the beam of high-energy neutrinos of cosmic origin that can be separated from atmospheric neutrinos at TeV energies and above. We will discuss the surprising observation that extragalactic cosmic ray accelerators dominate nearby Galactic sources with an energy flux that is comparable to that of high-energy photons. We will discuss the emergence of their sources after a decade of IceCube observations and in multimessenger campaigns. Importantly for this meeting, cosmic neutrinos provide us with a PeV-energy beam for neutrino physics.

---

31 July
9:45am
R: Wasatch A/B

Earth's matter effect in neutrino oscillation

Sanjib Kumar Agarwalla, Institute of Physics, Bhubaneswar
email: sanjib@iopb.res.in

No abstract provided.

Current Understanding of the Earth's Core

30 July
11:00am
R: Wasatch A/B

Francis Nimmo, UCSC
email: fnimmo@ucsc.edu

The Earth's core may be divided into two main regions: a solid inner core; and a liquid outer core. At the base of the outer core is a seismologically anomalous layer, likely denser than the liquid above. There may also be a low-density layer at the top of the outer core. The solid inner core is divided into two regions: a seismically anisotropic inner zone, and an isotropic layer on top. Although mainly composed of Fe, the core also contains 5% Ni and one or more light elements. Light element candidates include C,S,Si,O and H. Of these, O is almost certainly present; S or Si are plausible; and C and H are considered less likely. The core may also contain small amounts of noble gases. Radioactive K in the core could affect its cooling history, but current estimates suggest a core K concentration of 30ppm - too small to have a significant effect.

---

30 July
11:25am
R: Wasatch A/B

Neutrino Tomography of the Earth: the Potential of ORCA Detector

Francesco Caqpozzi[1] and **Serguey Petcov**[2]

[1]IFIC, Unicersity of Valencia, Spain; [2]SISSA/INFN, Trieste, Italy

email: [1]fcapozzi@ific.uv.es[2]petcov@sissa.it

Using PREM as a reference model for the Earth density distribution we present results on the sensitivity of ORCA detector to deviations of the Earth i) outer core (OC) density, ii) inner core (IC) density, iii) total core density, and iv) mantle density, from their respective PREM densities. The results are obtained in EPJ C82 (2022) 461 by studying the effects of the Earth matter on the oscillations of atmospheric ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$. We show that the ORCA sensitivity to the OC, IC, core and mantle densities depends strongly on the type of systematic uncertainties used in the analysis, on the value of the atmospheric neutrino mixing angle θ_{23}, on whether the Earth mass constraint is implemented or not, and on the way it is implemented, and on the type - with normal ordering (NO) or inverted ordering (IO) - of the light neutrino mass spectrum. We show, in particular, that in the "most favorable" NO case of implemented Earth mass constraint, "minimal" systematic errors and $\sin^2\theta_{23} = 0.58$, ORCA can determine, e.g., the OC (mantle) density at 3σ C.L. after 10 years of operation with an uncertainty of (-18%)/+15% (of (-6%)/+8%). In the "most disfavourable" NO case of "conservative" systematic errors and, e.g., $sin^2\theta_{23} = 0.50$ and 0.58 the uncertainties read, respectively: (-37)%/+30% and (-30%)/+24% ((-13%)/+16% and (-11%/+14%)). We find also that the sensitivity of ORCA to the OC, core and mantle densities is significantly worse for IO neutrino mass spectrum.

Current Understanding of Inner Core Structure and Open Questions

30 July
11:50am
R: Wasatch A/B

Keith Koper, University of Utah

email: koper@seis.utah.edu

Seismic imaging of the structure of Earth's inner core remains a challenging topic. The inner core occupies ¡ 1% of Earth's volume and the few seismic waves that do sample it can be significantly influenced by heterogeneities in the overlying crust and mantle. Furthermore, the seismic sources and receivers used in imaging the inner core are located at or near (¡ 700 km depth) Earth's surface and are irregularly distributed—most seismometers are deployed on land and most earthquakes occur near tectonic plate boundaries. Here I review the current standard model of inner core structure and describe some of the outstanding questions such as topography on the inner core boundary, hemisphericity, the innermost inner core, and shear velocity in the inner core.

---

30 July
12:15am
R: Wasatch A/B

Superionic H-bearing iron alloys in the Earth's inner core

Wenzhong Wang, University College London
email: wenzhong.wang@ucl.ac.uk

Earth's core plays a fundamental role in the evolution and habitability of our planet. Understanding its composition is key to interpreting the history of Earth's accretion. The density model suggests that the Earth's core is predominantly composed of iron (or iron-nickel alloy) with several percent of light elements, such as Si, S, C, O, and H, but their abundances in the Earth's core remain highly debated. Seismic observations may provide important constraints on the chemical compositions of Earth's core. It was revealed that Earth's inner core transmits shear waves at anomalously low velocity. Although considerable efforts have been devoted to understanding this phenomenon in the past two decades, there is no one solution model that can match all seismic observations and geochemical constraints. In this talk, I will introduce our recent findings on H-bearing alloys under inner-core conditions. The superionic state of the inner core can explain the observed density and velocities simultaneously. Our findings reveal that hydrogen is a fundamental light element in the Earth's core.

Unstable structure and dynamics in Earth's deepest mantle

30 July
9:30am
R: Wasatch A/B

Mingming Li, Arizona State University
email: mingming.li@asu.edu

In Earth's deepest mantle, there are two huge structures with anomalously lower seismic velocities, and perhaps different compositions, than their surroundings. One such structure is found beneath Africa and the other is beneath the Pacific Ocean. They are often called "Large Low Velocity Provinces". These structures are footprints of Earth's long-term evolution. By examining their morphology and physical-chemical properties, we can greatly improve our understanding of how the planet evolved in the past 4.5 billion years. Through an exhaustive analysis of previous seismic images of Earth's mantle, we discovered that the African anomaly is about 1,000 km taller than the Pacific anomaly. By performing mantle convection simulations with high-performance computers, we find that the most significant control on the maximum height that a compositionally distinct structure can reach is its density. These results further suggests that the Africa anomaly is unstable because it is not dense enough, in which case it may have been rising up in recent geological time.

---

30 July
9:30am
R: Wasatch A/B

Current understanding of the core-mantle boundary and open questions

Mike Thorne, University of Utah
email: michael.thorne@utah.edu

The core-mantle boundary (CMB) region is both a compositional and thermal boundary layer with the largest density contrast anywhere in the planet. As a result, the structures found within the lowermost mantle are as complex as those found on the Earth's surface. In this presentation we review the major features that have been identified from seismological studies. We review features at (1) the largest (¿ 1000 km) scales as revealed through seismic tomography of body wave and normal modes (2) intermediate scales (10's to 1000 km) as revealed through waveform modeling, and (3) at the smallest scales (10s of km) as revealed through stochastic studies. At the largest scales two Large Low Velocity Provinces (LLVPs) beneath Africa and the Pacific Ocean dominate the tomographic images. These two features are surrounded by high seismic wave velocity regions that are consistent with remains of the past 200 million years of subduction. At the largest scales, D" discontinuity structure is consistently observed in the high velocity regions, but has also been observed within the LLVP's at an apparently shallower depth. We discuss the nature of the LLVP's, their possible origins, and the ongoing debate surrounding what they physically represent. At the intermediate scales, multiple features have been observed, including core rigidity zones (CRZs), ultra-high velocity zones (UHVZs), and ultra-low velocity zones (ULVZs). Of these features, the ULVZs have received the most attention and appear to occupy a significant portion of the CMB landscape, with as much as 20% of the CMB region containing ULVZs inferred. Here we review current ideas about what these features are, where they are located, and their importance for whole Earth dynamic processes. At the smallest scales, the CMB area contains regions that generate the largest amplitude scattered arrivals. We discuss the locations where this scattered energy originates and the potential origins of the scatterers.

Neutrino oscillation tomography of the Earth and core composition with large water cherenkov detector

31 July
2:50pm
R: Wasatch A/B

Akimichi Taketa[1] and **Carsten Rott**[2]

[1]Earthquake Research Institute, University of Tokyo; [2]University of Utah

email: [1]taketa@eri.u-tokyo.ac.jp[2]carsten.rott@gmail.com

The neutrino oscillation probability depends on the electron density of the media and next generation neutrino detector will have the capability to resolve the earth's electron density distribution with some accuracy. If we combine the earth's matter density distribution and electron density distribution, then we can obtain the average chemical compositional distribution as Z/A ratio. Also if we assume some chemical composition model of the Earth, then we can obtain the matter density distribution of the Earth complimentaly. We will discuss about the possibility to measure the compositional distribution of the Earth using next generation large water cherenkov detector.

Validating the Earth's Core using Atmospheric Neutrinos with ICAL at INO

31 July
3:45pm
R: Wasatch A/B

Anil Kumar[1] and **Sanjib Kumar Agarwalla**[2]

[1]Insitute of Physics, Bhubaneswar. Homi Bhabha National Institute, Mumbai; [2]Institute of Physics, Bhubaneswar, HBNI, Mumbai, UW Madison and WIPAC, USA

email: [1]anil.k@iopb.res.in[2]sanjib@iopb.res.in

The Iron Calorimeter (ICAL) detector at the proposed India-based Neutrino Observatory (INO) aims to detect atmospheric neutrinos and antineutrinos separately in the multi-GeV range of energies and over a wide range of baselines. By utilizing its charge identification capability, ICAL can efficiently distinguish μ^- and μ^+ events. Atmospheric neutrinos passing long distances through Earth can be detected at ICAL with good resolution in energy and direction, which enables ICAL to see the density-dependent matter oscillations experienced by upward-going neutrinos in the multi-GeV range of energies. In this work, we explore the possibility of utilizing neutrino oscillations in the presence of matter to extract information about the internal structure of Earth complementary to seismic studies. Using good directional resolution, ICAL would be able to observe 331 μ^- and 146 μ^+ core-passing events with 500 kt·yr exposure. With this exposure, we show for the first time that the presence of Earth's core can be independently confirmed at ICAL with a median $\Delta\chi^2$ of 7.45 (4.83) assuming normal (inverted) mass ordering by ruling out the simple two-layered mantle-crust profile in theory while generating the prospective data with the PREM profile. We observe that in the absence of charge identification capability of ICAL, this sensitivity deteriorates significantly to 3.76 (1.59) for normal (inverted) mass ordering.

Measuring the Earth's outer core composition using neutrino oscillations

31 July
4:10pm
R: Wasatch A/B

Joao Coelho, Tufts University
email: joao.coelho@tufts.edu

No abstract submitted.

---

31 July
4:35pm
R: Wasatch A/B

Observing the Earth's Core with Neutrino Oscillations

Rebekah Pestes[1] and **Peter Denton**[2]

[1]Virginia Tech; [2]Brookhaven National Laboratory

email: [1]rebhawk8@vt.edu[2]peterbd1@gmail.com

Neutrinos change flavor as they travel, and this probability depends on the density of electrons in the material they are traveling through. So, we can use neutrinos produced in the atmosphere by cosmic rays to tell us about the density of electrons in the Earth. In this talk, I will present our simulations of this phenomenon that we did in determining the sensitivity of the Deep Underground Neutrino Experiment (DUNE) to the size of the Earth's core.

Neutrino Earth tomography in DUNE

31 July
5:00pm
R: Wasatch A/B

Kevin Kelly[1], Pedro Machado[2], Ivan Martinez Soler[3], Yuber Perez-Gonzalez [4]

[2]Fermilab; [3]Harvard University; [4]Durham U., IPPP

email: [1]kkelly942@gmail.com[2]acciolyp@gmail.com [3]imartinezsoler@fas.harvard.edu [4]yuber.f.perez-gonzalez@durham.ac.uk

This talk will show how the Earth's density profile can be measured in the DUNE experiment using atmospheric neutrinos. After crossing the Earth, neutrinos give us access to a rich oscillation phenomenology that strongly depends on the matter potential sourced by the Earth. By performing a detailed simulation of the event reconstruction capabilities of liquid argon time projection chambers, where we have included the particle identification and the nuclear effects, we find that DUNE can measure the Earth's total mass at 8.4% precision with an exposure of 400 kton year. In this result, we also include the different uncertainties that affect the atmospheric neutrino flux. Considering an effective Earth model with 3 layers, we have explored the sensitivity to each layer by combining DUNE with external measurements of the total mass and the moment of inertial of the Earth. Our analysis indicates that the core, lower mantle, and upper mantle densities can be determined with 8.8%, 13%, and 22% precision for the same exposure.

Author Index