Cosmic Ray Archaeology

Discovery of a big void in Khufu’s Pyramid by observation of cosmic-ray muons

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Summary
What Are Muons?

- Heavier version of the electron
- Generated by cosmic ray showers in the upper atmosphere
- Number of muons reaching detector depends on matter passed through

Cosmic ray particle showers generating muons in the earth’s atmosphere
The Great Pyramid
- Khufu’s Pyramid

- Used muons to image the great pyramid
  - Found muon excess indicating new void

- 3 different institutions involved:
  - Nagoya University
  - High Energy Accelerator Research Organization (KEK)
  - Commissariat à l’Energie Atomique et aux Energies Alternatives (CEA)

Side view of Khufu’s pyramid including detector positions for each institution
How Muons are Detected

- Multiple detectors overlap
- Coincidence required for muon detection
- Observed angle determined by distance between detectors

Diagram illustrating solid angle observed
There are three common detection methods for muons:

- **Nuclear Emulsion Films**
- **Scintillator Hodoscopes**
- **Gas Detectors**

Graphic representation of a nuclear emulsion film

Graphic representation of a scintillator hodoscope

Graphic representation of the gas detector used.
Three Different Data Analysis Models were Used

- Three independent simulations
  - Geant4
  - Monte Carlo
  - CRY/Geant4

- Detailed 3D model

- Normalized data to these models

3D model of the pyramid which was compared with data
Comparison with Previous Work
Other Surveys of The Great Pyramid

- Microgravimetry surveys
  - Measurement of slight variations in gravity caused by variations in the amount of matter
  - Attempted to find the ‘hidden room’ but found sand instead

- Ground penetrating radar survey
  - Usage of radar signals to create an image of the surface
  - Suggested that there might be an unknown corridor
  - Neither confirmed nor refuted
Other Muon Detector Applications

- In particle accelerators, detection of muons captures data from particle collisions
- Spark chambers used as muon detectors in Khafre’s Pyramid
  - Concluded no new chambers with similar volumes to four known chambers
- Homeland security
  - Muon tomography: probe through shielded material by measuring deflections of cosmic ray muons
- Other archaeological sites: Rome, Naples, Teotihuacan Pyramid
Critical Analysis
Scientific Validity

- Able to detect known structures with this technology
- Three consistent independent detections of the void, compared to detailed simulations

Remaining questions:

- Why only use a subset of nuclear emulsion film data?
- Why enlarge solid angle when using scintillator hodoscopes?
IMPORTANCE

✧ The first confident detection of an inner structure in this pyramid since the 19th century.
✧ Also the first time a void has ever been detected from outside a structure.
✧ This paper furthers efforts in the fields mentioned previously:
  ✧ Other archaeological surveys around the world
  ✧ High energy physics (particle accelerators)
  ✧ Studies using this idea were used for nuclear security
**BROAD INTEREST**

- Of interest to both the archaeological & physics communities

- Overall, language of paper is clear, concise and avoids jargon.

- However, methods section could be made more accessible to non-experts by adding more diagrams

Side view of the pyramid, including the newly discovered void
Conclusions
Author’s Conclusions

- Discovered large void of same cross-sectional area as Grand Gallery, minimum length 30 m
- Void’s purpose and exact shape still unclear
- Void could consist of one or several adjacent voids, either inclined or horizontal

Inner structure of the pyramid, including possible orientations of the void
Our Conclusion

-we recommend this paper for publication
- scientifically valid
- important
- broad interest

-suggest the small edits mentioned previously
- justify methods

Cross-sectional interior view of the 3d model of the Great pyramid
Work That Followed This Paper

- Scopus field weighted citation impact: 5.28
  - Average paper weight impact is 1.0, for reference
- Cited by 55 other papers
- Among those:
  - The MEV Project: high-resolution telescope for muography of Etna Volcano
  - Neutron Imaging at LANSCE: imaging of metallic and ceramic nuclear fuels
Reference List


