Tsunami from Plume-Forming Collisional Airbursts

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.
First direct observation of atmospheric collision: Shoemaker-Levy 9 comet crash: Jupiter, 1994

“Point source” explosion is not a good airburst approximation
Plumes from collisional airbursts: Emergent phenomenon
Discovered in 1993 by computation of Shoemaker-Levy 9

Visible From Earth

Behind Jupiter

Cloud Tops

67 seconds after impact

1000 km
Airburst is a line explosion that ejects a plume: Observational validation by Shoemaker-Levy 9 impact.
Plumes and line explosions on Earth

Near-Earth Objects
The United Nations International Conference

Editor
John L. Remo
“Tsunami” on Jupiter
“Tsunami” on Jupiter
“Tsunami” on Jupiter
Hammel, Heidi B. et al.,
“HST Imaging of Atmospheric Phenomena
Created by the Impact of Comet Shoemaker-Levy 9"

Waves: “In images taken within 3 hours of the larger impacts, we detected transient ‘rings’ that are most likely caused by atmospheric waves. The most dramatic example was the multiple ring system created by the large G fragment. The circularity of the rings suggests that they are waves; debris features are asymmetric.”

“Images of Jupiter taken by the Hubble Space Telescope (HST) reveal two concentric circular rings surrounding five of the impact sites from comet Shoemaker-Levy 9 (SL9). The rings are visible 1.0 to 2.5 hours after the impacts. The outer ring expands at a constant rate of 450 ms⁻¹. The inner ring expands at about half that speed. The rings appear to be waves....”

Ingersoll and Kanamori have argued that internal gravity waves trapped in a stable layer within the putative water cloud are the only waves that can match the observations.
A. P. Ingersoll & H. Kanamori: Waves from the SL9 impacts

Time-Distance Curve (Travel-Time Curve)

- Acoustic: $v = 720$ m/s
- Solar: $v = 130$ m/s
- $v = 450$ m/s (10x solar)

Radius (km) vs. Time after impact (s)
A. P. Ingersoll & H. Kanamori: Waves from the SL9 impacts

Time-Distance Curve (Travel-Time Curve)

Radius (km)

- △ A
- ■ E
- ● G
- ○ Q1
- ◆ R

- v = 720 m/s (10x solar)
- v = 210 m/s
- v = 130 m/s (solar)

Time after impact (s)
A. P. Ingersoll & H. Kanamori: *Waves from the SL9 impacts*

**Time-Distance Curve (Travel-Time Curve)**

- **Acoustic**: $v = 720 \text{ m/s}$
- **Solar**: $v = 130 \text{ m/s}$
- **Data points**
  - A
  - E
  - G
  - Q1

**Graph:**
- Radius (km) on the y-axis
- Time after impact (s) on the x-axis
- Data points with error bars

**Inset:**
- Graph showing detailed data points

**Legend:**
- Symbols for data points
A. P. Ingersoll & H. Kanamori: Waves from the SL9 impacts

Time-Distance Curve (Travel-Time Curve)

Radius (km)

- A
- E
- G
- Q1

acoustic (v=720 m/s)
v=450 m/s (10x solar)
v=210 m/s
solar (v=130 m/s)

Time after impact (s)
Reflection?
Sliding ejecta?
Tunguska Yield Estimates

Three ways to generate seismic impulse: \(7 \times 10^{18}\) dyne-cm

The earth has a \(\beta\) for seismic coupling time scale

1000 Mton \(\beta = 1\)
Turco et al., 1982

12.5 Mton \(\beta \approx 80\)
Ben-Menahem, 1975

3 Mton \(\beta \approx 300\)
Boslough & Crawford, 1997
Distribution of bright night skies, June 30 – July 1, 1908 (I.T Zotkin & A.L. Tchijevsky)
The coast was inundated up to 50 meters inland and unexpectedly swept many fishermen off of the Montrose Harbor piers, killing seven.
Rissaga a Ciutadella (2006)
“...even during the strongest events, the atmospheric pressure oscillations at these scales typically reach only a few hPa that correspond only to a few cm of sea level change.”
S. Monserrat et al.,
"Meteotsunamis: atmospherically induced destructive ocean waves in the tsunami frequency band."
Nat. Hazards Earth Syst. Sci., 6, 1035–1051, 2006

“...even during the strongest events, the atmospheric pressure oscillations at these scales typically reach only a few hPa that correspond only to a few cm of sea level change.”

**3 Mton Tunguska-scale impact**

Plume impulse = $7 \cdot 10^{18}$ dyne-s within 1 minute
(Boslough & Crawford, (1997)

Mean force for 60 s = $1.2 \cdot 10^{17}$ dynes

Area within sound speed of epicenter at 60 s = 1200 km$^2$

Mean overpressure = 10 mbar = 10 hPa
Consequently, these atmospheric fluctuations can produce a significant sea level response only when some form of resonance occurs between the ocean and the atmospheric forcing.

**Proudman resonance**

\[ U = c, \] i.e. the atmospheric disturbance translational speed \( U \) equals the longwave phase speed \( c = \sqrt{gh} \) of ocean waves

**Froude number** \( (Fr = U/c) \)

Coupling is strong when \( Fr \approx 1.0 \)
4.6-km deep ocean has same Fr as Jupiter
Conclusion

• Tunguska-scale plume-forming impact can generate reaction impulse that raises atmospheric pressure over a large area on time scale sufficiently close to the Proudman resonance in deep water (>4 km) to produce dangerous meteotsunami.

• This effect needs to be quantified and included in NEO hazard assessment.
"I don't know what this is, but it looks like a squashed comet."
--Carolyn Shoemaker, March 24, 1993