1
00:00:00,520 --> 00:00:03,640
>> Announcer: NASA's Jet
Propulsion Laboratory presents

2
00:00:03,820 --> 00:00:05,900
the von Karman Lecture,
a series of talks

3
00:00:05,938 --> 00:00:07,707
by scientists and engineers

4
00:00:07,740 --> 00:00:11,244
who are exploring our
planet, our solar system,

5
00:00:11,277 --> 00:00:13,279
an all that lies beyond.

6
00:00:25,424 --> 00:00:27,493
>> Hey, good evening,
ladies and gentleman.

7
00:00:27,526 --> 00:00:28,761
How is everyone tonight?

8
00:00:28,794 --> 00:00:29,629
[audience cheers]

9
00:00:29,662 --> 00:00:30,497
Excellent.

10
00:00:32,231 --> 00:00:33,433
Well, anyway, thank you guys

11
00:00:33,466 --> 00:00:34,901
all so much for
coming out tonight.

12

00:00:34,934 --> 00:00:38,438
Volcanoes have helped transform
the surface of the earth,

13
00:00:38,471 --> 00:00:40,606
the other terrestrial
planets, and the moon.

14
00:00:40,639 --> 00:00:43,643
However, the biggest volcanic
eruptions in the solar system

15
00:00:43,676 --> 00:00:47,780
are taking place not on Earth
but on Io, a moon of Jupiter.

16
00:00:47,813 --> 00:00:50,750
This wonder of the solar system
is a fascinating laboratory

17
00:00:50,783 --> 00:00:54,387
where powerful eruptions
result from tidal heating.

18
00:00:54,420 --> 00:00:56,923
Despite multiple spacecraft
visits and spectacular

19
00:00:56,956 --> 00:00:59,759
new observations with
Earth-based telescopes,

20
00:00:59,792 --> 00:01:02,762
some of the biggest questions
about Io's volcanism

21
00:01:02,795 --> 00:01:04,464
remain unanswered.

22
00:01:04,497 --> 00:01:06,999

Getting the answers
requires a few things:

23
00:01:07,032 --> 00:01:08,434
understanding the difficulties

24
00:01:08,467 --> 00:01:10,837
of remote sensing of
volcanic activity,

25
00:01:10,870 --> 00:01:13,339
innovating a new approach
to instrument design,

26
00:01:13,372 --> 00:01:15,641
and ultimately, returning to Io.

27
00:01:15,674 --> 00:01:18,044
Our guest tonight will
describe how studying volcanoes

28
00:01:18,077 --> 00:01:20,179
on Earth leads to a
clearer understanding

29
00:01:20,212 --> 00:01:24,083
of how Io's volcanoes work
and how best to study them.

30
00:01:24,116 --> 00:01:26,152
Tonight's guest is
a research scientist

31
00:01:26,185 --> 00:01:29,155
at volcanologist here at the
Jet Propulsion Laboratory.

32
00:01:29,188 --> 00:01:31,057
He received a doctorate
in volcanology

33
00:01:31,090 --> 00:01:34,393
from Lancaster University
in the UK in 1988

34
00:01:34,426 --> 00:01:37,130
and has been at JPL
for over 20 years.

35
00:01:37,163 --> 00:01:39,499
He was a member of
the Galileo NIMS team,

36
00:01:39,532 --> 00:01:41,868
is a co-investigator
on the Europa Clipper

37
00:01:41,901 --> 00:01:44,570
mapping-imaging
spectrometer for Europa,

38
00:01:44,603 --> 00:01:46,239
has written over 100 papers

39
00:01:46,272 --> 00:01:49,008
on observing and understanding
volcanic processes,

40
00:01:49,041 --> 00:01:50,877
and is the, pardon me,

41
00:01:50,910 --> 00:01:52,879
and is the author
of Volcanism on Io:

42
00:01:52,912 --> 00:01:54,380
A Comparison with Earth,

43
00:01:54,413 --> 00:01:56,849

published by the Cambridge
University Press.

44
00:01:56,882 --> 00:01:58,417
He continues to be
engaged in research

45
00:01:58,450 --> 00:02:00,486
into volcanic
eruption processes,

46
00:02:00,519 --> 00:02:03,122
spacecraft emission and
instrumentation development,

47
00:02:03,155 --> 00:02:06,092
and fieldwork on volcanoes
around the world.

48
00:02:06,125 --> 00:02:08,828
He was also a co-recipient
of the NASA Software

49
00:02:08,861 --> 00:02:11,330
of the Year Award for
the Autonomous Science

50
00:02:11,363 --> 00:02:14,200
Craft Experiment, which
successfully demonstrated

51
00:02:14,233 --> 00:02:17,303
science-driven full
spacecraft autonomy.

52
00:02:17,336 --> 00:02:20,206
His love of volcanoes
is truly undeniable.

53
00:02:20,239 --> 00:02:23,609

Every year, he sends his
PhD advisor a birthday card

54
00:02:23,642 --> 00:02:27,814
depicting a work of great
art improved with a volcano.

55
00:02:29,848 --> 00:02:31,184
Ladies and gentlemen,

56
00:02:31,217 --> 00:02:33,920
please help me welcome tonight's
guest, Dr. Ashley Davis.

57
00:02:33,953 --> 00:02:36,956
[audience applauds]

58
00:02:40,960 --> 00:02:44,063
>> Thank you all
very much for coming.

59
00:02:47,032 --> 00:02:49,435
The surface of the moon

60
00:02:49,468 --> 00:02:52,104
and the surfaces of
the terrestrial planets

61
00:02:52,137 --> 00:02:55,508
have all been
extensively modified

62
00:02:55,541 --> 00:02:59,378
by extreme volcanic activity
in their distant pasts,

63
00:02:59,411 --> 00:03:03,650
and these large eruptions are
mostly unknown in the manner

64
00:03:04,984 --> 00:03:08,721
in which they emplaced
large, vast fields of lava.

65
00:03:10,756 --> 00:03:12,325
But there was one place
in the solar system

66
00:03:12,358 --> 00:03:16,429
where such voluminous,
powerful, extensive flows,

67
00:03:18,264 --> 00:03:20,533
volcanic eruptions
are taking place,

68
00:03:20,566 --> 00:03:23,803
and that is the Jovian moon Io.

69
00:03:23,836 --> 00:03:26,406
Io holds some fascinating views

70
00:03:29,108 --> 00:03:33,546
of how Earth might have
erupted in its distance past,

71
00:03:33,579 --> 00:03:35,681
is a key to understand
the evolution

72
00:03:35,714 --> 00:03:38,318
of the large Jovian satellites,

73
00:03:39,118 --> 00:03:40,586
and is a great template

74
00:03:40,619 --> 00:03:45,291
for looking for volcanically
active exoplanets.

75
00:03:45,324 --> 00:03:49,229
It's truly an amazing
place to a volcanologist.

76
00:03:50,329 --> 00:03:52,565
I think I have a
pretty cool job,

77
00:03:52,598 --> 00:03:55,568
because I study
volcanoes for NASA.

78
00:03:55,601 --> 00:03:58,938
And although this usually
means that I spend

79
00:03:58,971 --> 00:04:01,440
most of my time staring
at the computer screen

80
00:04:01,473 --> 00:04:04,844
and crunching data and
looking at remote sensing

81
00:04:04,877 --> 00:04:07,546
observations of
volcanic eruptions,

82
00:04:07,579 --> 00:04:08,781
occasionally, they let me out

83
00:04:08,814 --> 00:04:11,584
to go and play on a
real volcano somewhere.

84
00:04:11,617 --> 00:04:12,818
And it's a great job.

85

00:04:12,851 --> 00:04:14,420
It's very exciting,
and it's taken me

86
00:04:14,453 --> 00:04:16,522
to the ends of the earth.

87
00:04:18,123 --> 00:04:21,227
This is in the background
here we have Mount Erebus.

88
00:04:21,260 --> 00:04:24,163
It is the world's most
suddenly active volcano

89
00:04:24,196 --> 00:04:26,065
in Antarctica.

90
00:04:26,098 --> 00:04:29,669
The summit there is a crater
with a lava lake in it.

91
00:04:29,702 --> 00:04:33,806
This is in Ethiopia, and
again, over on the right,

92
00:04:33,839 --> 00:04:38,011
we see another lava lake on
a volcano called Erta Ale.

93
00:04:41,046 --> 00:04:44,283
Now, it's important to
think about volcanoes

94
00:04:44,316 --> 00:04:47,153
and what they mean for
the evolution of a planet,

95
00:04:47,186 --> 00:04:49,522
but apart from that,

96
00:04:49,555 --> 00:04:53,859
volcanic eruptions are
an agent for change

97
00:04:53,892 --> 00:04:57,997
which can affect millions
of people very quickly.

98
00:04:58,030 --> 00:05:01,534
This is Mount St.
Helens erupting in 1980,

99
00:05:02,701 --> 00:05:05,705
and on Earth, over 250
million people live

100
00:05:05,738 --> 00:05:09,442
within 20 kilometers
of a volcano

101
00:05:09,475 --> 00:05:12,812
that can erupt
like this.

102
00:05:12,845 --> 00:05:14,313
Apart from that,

103
00:05:14,346 --> 00:05:16,615
moving away from
the human element,

104
00:05:16,648 --> 00:05:20,820
volcanoes are a window into
the interior of the earth,

105
00:05:22,354 --> 00:05:24,023
or any other planet.

106

00:05:24,056 --> 00:05:27,927
They are an indication
of internal heating

107
00:05:27,960 --> 00:05:30,296
which has melted
the upper mantle,

108
00:05:30,329 --> 00:05:32,298
and they conveniently
transport material

109
00:05:32,331 --> 00:05:34,667
from the inside of a
planet to the surface

110
00:05:34,700 --> 00:05:39,071
where it can be observed with
instruments on a spacecraft.

111
00:05:39,104 --> 00:05:42,708
And there are many styles of
volcanic activity on Earth,

112
00:05:42,741 --> 00:05:44,977
and I've been spending
most of my time looking

113
00:05:45,010 --> 00:05:48,181
at low-viscosity
basalt-type eruptions

114
00:05:49,548 --> 00:05:50,717
at lava lakes.

115
00:05:51,850 --> 00:05:55,588
A lava lake is the top
of a column of magma

116
00:05:55,621 --> 00:05:58,657

connected to a magma chamber.

117
00:05:58,690 --> 00:06:02,128
It's an open system around
which magma circulates,

118
00:06:02,161 --> 00:06:03,596
and they're quite rare on Earth.

119
00:06:03,629 --> 00:06:06,198
They tend to crop up in
quite extreme environments,

120
00:06:06,231 --> 00:06:09,034
although there is a
big one in Hawaii now.

121
00:06:09,067 --> 00:06:13,239
But they're very useful for
studying basaltic processes.

122
00:06:15,841 --> 00:06:18,077
I've been studying
these on Earth

123
00:06:18,110 --> 00:06:21,781
to better understand
what's happening on Io.

124
00:06:23,182 --> 00:06:25,651
Now, the Galilean
satellites were discovered

125
00:06:25,684 --> 00:06:29,756
by the great Italian
astronomer, Galileo Galilei.

126
00:06:32,758 --> 00:06:35,194
On the ninth of January 1610,

127
00:06:38,163 --> 00:06:41,267
Galileo noted in his notebook

128
00:06:41,300 --> 00:06:44,770
that using this new Dutch
invention, the telescope,

129
00:06:44,803 --> 00:06:46,639
he observed Jupiter

130
00:06:46,672 --> 00:06:50,643
and noted these little
stars close to Jupiter,

131
00:06:50,676 --> 00:06:53,212
and noted that over
the next few nights,

132
00:06:53,245 --> 00:06:55,581
the position of these
dots would change,

133
00:06:55,614 --> 00:06:57,149
and came to the conclusion

134
00:06:57,182 --> 00:06:59,351
that these were
actually orbiting...

135
00:06:59,384 --> 00:07:02,354
These were actually
moons orbiting Jupiter.

136
00:07:02,387 --> 00:07:03,556
So we can jump forward

137
00:07:03,589 --> 00:07:06,559
400 years go the
Voyager spacecraft.

138
00:07:07,659 --> 00:07:10,496
There were two of these
built here at JPL.

139
00:07:10,529 --> 00:07:14,200
And Voyager flew through
the Jupiter system,

140
00:07:15,434 --> 00:07:17,002
and on Io,

141
00:07:17,035 --> 00:07:18,304
made one of the
greatest discoveries

142
00:07:18,337 --> 00:07:20,606
of planetary science,

143
00:07:20,639 --> 00:07:24,777
that Io had these
large volcanic plumes.

144
00:07:24,810 --> 00:07:27,980
And this was a real revolution
in our understanding

145
00:07:28,013 --> 00:07:31,016
of the outer solar system,
because up to this point,

146
00:07:31,049 --> 00:07:33,352
it was generally
thought that the moons

147
00:07:33,385 --> 00:07:37,557
of the outer solar system
planets were small, dead worlds

148

00:07:38,957 --> 00:07:42,495
where over geological time,
the geological processes

149
00:07:42,528 --> 00:07:43,896
that were changing them

150
00:07:43,929 --> 00:07:47,032
had basically been
damped down into nothing.

151
00:07:47,065 --> 00:07:50,436
They were small, cold ice balls.

152
00:07:50,469 --> 00:07:55,207
But here we have Io being
a dynamic, evolving world.

153
00:07:55,240 --> 00:07:59,345
A follow-up mission to Voyager
was fittingly called Galileo,

154
00:08:00,412 --> 00:08:02,481
and I was on the Near Infrared

155
00:08:02,514 --> 00:08:04,917
Mapping Spectrometer team, NIMS.

156
00:08:04,950 --> 00:08:07,820
And here we see
in the lower right

157
00:08:07,853 --> 00:08:10,556
an observation of Io with NIMS.

158
00:08:10,589 --> 00:08:12,825
NIMS is an instrument
that was particularly good

159

00:08:12,858 --> 00:08:17,029
at detecting the heat given
off from volcanic eruptions

160
00:08:18,664 --> 00:08:21,500
and sent back a lot of data.

161
00:08:21,533 --> 00:08:25,705
Now, the NIMS, the Galileo
main antenna didn't open,

162
00:08:26,605 --> 00:08:27,806
and so there was a restriction

163
00:08:27,839 --> 00:08:29,542
on the amount of
data that came back.

164
00:08:29,575 --> 00:08:32,478
And so there are
still some gaps on Io

165
00:08:32,511 --> 00:08:35,948
that need to be filled
in terms of coverage.

166
00:08:35,981 --> 00:08:40,152
So, here we have the four
large Galilean satellites

167
00:08:41,486 --> 00:08:45,391
as imaged by the imaging system
on the Galileo spacecraft:

168
00:08:46,692 --> 00:08:49,895
Io, Europa, Ganymede,
and Callisto.

169
00:08:49,928 --> 00:08:54,100
Io is closest to Jupiter, and

Callisto is furthest away.

170
00:08:55,801 --> 00:08:58,837
And here we have Io, as
seen by the camera system

171
00:08:58,870 --> 00:09:01,107
on the Galileo spacecraft.

172
00:09:01,974 --> 00:09:04,643
And the colors of Io's surface

173
00:09:04,676 --> 00:09:07,046
are diagnostic of composition.

174
00:09:07,079 --> 00:09:10,382
If it's yellow,
it's rich in sulfur.

175
00:09:10,415 --> 00:09:14,353
White areas are rich
in sulfur dioxide.

176
00:09:14,386 --> 00:09:17,656
What's of great interest
to me are the black areas

177
00:09:17,689 --> 00:09:19,124
and the red areas.

178
00:09:19,157 --> 00:09:21,193
The black areas are areas
of silicate volcanism.

179
00:09:21,226 --> 00:09:22,895
This is where
material like basalt

180
00:09:22,928 --> 00:09:25,130

is being erupted
onto the surface.

181
00:09:25,163 --> 00:09:26,532
The red areas are thought to be

182
00:09:26,565 --> 00:09:29,134
short-chain sulfur allotropes,

183
00:09:29,167 --> 00:09:33,339
which are evidence of active
or ongoing volcanic activity.

184
00:09:34,740 --> 00:09:38,411
So every black or red area
on this, in this image

185
00:09:39,611 --> 00:09:43,349
is an active or very
recently active volcano.

186
00:09:46,718 --> 00:09:48,020
Now, the amazing thing about Io

187
00:09:48,053 --> 00:09:50,489
is that it's actually
volcanic at all.

188
00:09:50,522 --> 00:09:52,024
Here we have Io
next to the moon.

189
00:09:52,057 --> 00:09:54,860
And the moon was
once very volcanic.

190
00:09:54,893 --> 00:09:56,895
These dark areas are the mare,

191

00:09:56,928 --> 00:10:01,100
and these are layers of
basalt many kilometers thick.

192
00:10:02,534 --> 00:10:06,472
But the moon is, as far as we
can tell, volcanically dead.

193
00:10:06,505 --> 00:10:09,975
And this is because what
drove volcanism on the moon

194
00:10:10,008 --> 00:10:13,312
and what continues to
drive volcanism on Earth

195
00:10:13,345 --> 00:10:17,850
is internal heating by the
decay of radioisotopes.

196
00:10:17,883 --> 00:10:19,585
This is material
that was incorporated

197
00:10:19,618 --> 00:10:23,822
into the planets and
moons when they formed.

198
00:10:23,855 --> 00:10:25,724
Now, the laws of physics dictate

199
00:10:25,757 --> 00:10:29,929
that a small body loses heat
faster than a large body does.

200
00:10:31,863 --> 00:10:33,932
So over billions of years,

201
00:10:33,965 --> 00:10:36,369
the moon and Mercury and Mars

202
00:10:37,869 --> 00:10:40,906
lost their internal
heat to space.

203
00:10:40,939 --> 00:10:44,510
The heat that was driving
this vulcanological engine

204
00:10:44,543 --> 00:10:47,146
within each planet slowed down,

205
00:10:48,647 --> 00:10:50,849
and it eventually stopped,
and large-scale volcanism

206
00:10:50,882 --> 00:10:53,419
on these bodies was
stilled forever.

207
00:10:53,452 --> 00:10:54,987
So this is what happens

208
00:10:55,020 --> 00:10:58,691
with a small body with an
internal source of energy.

209
00:10:58,724 --> 00:11:01,360
With Io, something very
different is happening.

210
00:11:01,393 --> 00:11:03,028
Io's source of energy

211
00:11:03,061 --> 00:11:06,332
which drives its
volcanism is external.

212
00:11:09,334 --> 00:11:13,839

Io, Europa, and Ganymede
are in an orbital resonance.

213
00:11:13,872 --> 00:11:17,509
For every orbit that Ganymede
makes around Jupiter,

214
00:11:17,542 --> 00:11:19,378
Europa makes two orbits,

215
00:11:19,411 --> 00:11:21,513
and Io makes four orbits.

216
00:11:21,546 --> 00:11:24,450
So every time Io passes,
for example, Europa,

217
00:11:24,483 --> 00:11:28,153
Io gets a little kick,
and it's taken Io's orbit

218
00:11:28,186 --> 00:11:30,155
and changed it from
a circular orbit

219
00:11:30,188 --> 00:11:32,091
into a slightly
elliptical orbit,

220
00:11:32,124 --> 00:11:34,693
a bit more eccentric orbit.

221
00:11:34,726 --> 00:11:38,497
And Io gets twisted
each time it passes

222
00:11:38,530 --> 00:11:40,666
one of the other two satellites,

223

00:11:40,699 --> 00:11:44,470
and it's this tidal flexing
that generates heat within Io

224
00:11:44,503 --> 00:11:49,074
that manifests at the
surface as active volcanism.

225
00:11:49,107 --> 00:11:52,211
So it's an external source
driving this extraordinary level

226
00:11:52,244 --> 00:11:54,480
of volcanic activity on Io.

227
00:11:55,680 --> 00:11:58,383
It's an elegant cosmic
ballet, if you like,

228
00:11:58,416 --> 00:12:02,354
choreographed by the
immutable laws of physics.

229
00:12:03,522 --> 00:12:05,190
Now, just to put
the majestic scale

230
00:12:05,223 --> 00:12:08,127
of Io's volcanism into
some sort of context,

231
00:12:08,160 --> 00:12:09,895
this is the amount of material

232
00:12:09,928 --> 00:12:13,966
that is erupted from earth's
volcanoes every year.

233
00:12:13,999 --> 00:12:16,535
Most of this is erupted

on the ocean floor

234
00:12:16,568 --> 00:12:19,104
at the mid-ocean ridges.

235
00:12:19,137 --> 00:12:22,241
On Io, this is the amount
of material that's erupted

236
00:12:22,274 --> 00:12:26,645
every year to erase any
evidence of impact craters.

237
00:12:26,678 --> 00:12:28,347
There are no impact
craters on Io,

238
00:12:28,380 --> 00:12:31,984
unlike any other solid
body in the solar system.

239
00:12:32,017 --> 00:12:33,585
So there really is a
truly astonishing amount

240
00:12:33,618 --> 00:12:36,455
of volcanic activity
taking place.

241
00:12:37,789 --> 00:12:39,825
Over the years, we've
collected a lot of data

242
00:12:39,858 --> 00:12:44,029
from spacecraft, and
this is a mosaic compiled

243
00:12:44,062 --> 00:12:48,333
from the best Voyager and
Galileo spacecraft data,

244
00:12:48,366 --> 00:12:52,204
and basically, we've covered
most of Io at resolutions

245
00:12:52,237 --> 00:12:57,042
good enough to identify
volcanoes from their appearance

246
00:12:57,075 --> 00:12:59,645
and their thermal emission.

247
00:12:59,678 --> 00:13:03,516
And to this has been
added a growing dataset,

248
00:13:04,649 --> 00:13:07,085
an astonishing library
of observations obtained

249
00:13:07,118 --> 00:13:10,923
with large telescopes
based here on Earth.

250
00:13:10,956 --> 00:13:15,160
This is from the Keck
telescope in Hawaii.

251
00:13:15,193 --> 00:13:19,298
These are telescopes equipped
with adaptive optics.

252
00:13:19,331 --> 00:13:23,502
This is measuring the heat from
a whole series of hotspots.

253
00:13:25,136 --> 00:13:27,739
And so putting all of
these datasets together,

254
00:13:27,772 --> 00:13:31,810
we've been able to catalog
all of the volcanoes on Io

255
00:13:31,843 --> 00:13:34,847
and quantify their
thermal emission.

256
00:13:36,448 --> 00:13:40,619
This plot shows 250
volcanoes erupting on,

257
00:13:40,652 --> 00:13:44,890
which have been recently or
are currently erupting on Io.

258
00:13:44,923 --> 00:13:47,459
And these range in size
from areas of just a few

259
00:13:47,492 --> 00:13:52,030
hundred square meters to
vast multiple-kilometer areas

260
00:13:52,063 --> 00:13:54,366
of incandescent material.

261
00:13:54,399 --> 00:13:58,704
Rare thermal outbursts are
actually marked here by squares.

262
00:13:58,737 --> 00:14:01,006
These are rare and transient.

263
00:14:01,039 --> 00:14:03,542
So, the size of these symbols,

264
00:14:05,677 --> 00:14:07,846
the larger the symbol, the

more energy is coming out.

265
00:14:07,879 --> 00:14:11,850
This is actually on
a logarithmic scale.

266
00:14:11,883 --> 00:14:15,621
But the heat flow
from Io is not even.

267
00:14:15,654 --> 00:14:19,458
There are areas where we
see a deficit of heat flow

268
00:14:19,491 --> 00:14:21,393
and other areas where we
see a lot of heat flow.

269
00:14:21,426 --> 00:14:26,398
And this isn't really matched
very well to the models

270
00:14:26,431 --> 00:14:30,336
that we have of either
shallow or deep heating.

271
00:14:31,770 --> 00:14:35,807
So there's still a lot about
the way in which tidal heating

272
00:14:35,840 --> 00:14:39,945
is linked to the delivery
of lava at the surface.

273
00:14:42,414 --> 00:14:45,350
Well, let's take a look at some
of these amazing volcanoes.

274
00:14:45,383 --> 00:14:48,287
This is a great image

obtained by Galileo

275
00:14:48,320 --> 00:14:52,057
which shows a volcano
here called Prometheus.

276
00:14:53,591 --> 00:14:56,194
This is a volcano which
generates a large plume

277
00:14:56,227 --> 00:14:57,396
about 100 kilometers high

278
00:14:57,429 --> 00:14:59,231
which lays down this
circular deposit

279
00:14:59,264 --> 00:15:01,199
which is rich in sulfur dioxide.

280
00:15:01,232 --> 00:15:04,569
And in the middle of
this plume deposit

281
00:15:04,602 --> 00:15:08,340
is a lava flow field,
which was emplaced

282
00:15:08,373 --> 00:15:11,476
between the Voyager and
the Galileo missions

283
00:15:11,509 --> 00:15:14,212
in a period of about 16 years.

284
00:15:14,245 --> 00:15:17,416
So we can go in and take
a closer look at this.

285

00:15:17,449 --> 00:15:20,218
Here, we have the
flows at Prometheus,

286
00:15:20,251 --> 00:15:22,821
and for scale, we have an image

287
00:15:22,854 --> 00:15:26,025
of Earth's most
active basalt volcano.

288
00:15:27,425 --> 00:15:30,095
This is Kilauea in Hawaii.

289
00:15:30,128 --> 00:15:32,864
And this is the area of flows

290
00:15:32,897 --> 00:15:35,467
which was emplaced in
about the same time.

291
00:15:35,500 --> 00:15:37,469
So the area of flows here

292
00:15:37,502 --> 00:15:41,006
is well over a thousand
square kilometers,

293
00:15:42,407 --> 00:15:45,110
and it's, I don't know, over
2,000 square kilometers.

294
00:15:45,143 --> 00:15:47,412
It's about the area
of Rhode Island.

295
00:15:47,445 --> 00:15:50,415
And this was emplaced
in just 16 years.

296
00:15:50,448 --> 00:15:54,052
This is particularly
interesting volcano,

297
00:15:54,085 --> 00:15:58,123
because what we think
is happening here

298
00:15:58,156 --> 00:16:01,493
is that lava is coming
up at a vent here

299
00:16:04,863 --> 00:16:08,433
and then passing through
a lava cube system

300
00:16:08,466 --> 00:16:12,070
before erupting out at
distal ends of the flows,

301
00:16:12,103 --> 00:16:14,606
very much like what
we see in Hawaii.

302
00:16:14,639 --> 00:16:17,142
And a logical
explanation is lava tube

303
00:16:17,175 --> 00:16:19,411
transportation of new lava,

304
00:16:21,413 --> 00:16:23,315
which is a great way
of transporting lava

305
00:16:23,348 --> 00:16:26,451
a great distance without
it cooling and solidifying.

306

00:16:26,484 --> 00:16:29,955
But along the way, we see
these tantalizingly faint,

307
00:16:29,988 --> 00:16:32,924
small, thermal sources,
which could be breakouts

308
00:16:32,957 --> 00:16:34,659
onto the surface or skylights,

309
00:16:34,692 --> 00:16:36,495
which are holes in the
roof of a lava tube.

310
00:16:36,528 --> 00:16:37,596
And I'll certainly
be coming back

311
00:16:37,629 --> 00:16:39,898
and discussing those later.

312
00:16:42,500 --> 00:16:44,870
Io's most powerful volcano

313
00:16:44,903 --> 00:16:47,840
is in a feature
called Loki Patera.

314
00:16:48,807 --> 00:16:50,575
And the general consensus

315
00:16:50,608 --> 00:16:54,446
is that this is actually
a large lava lake,

316
00:16:54,479 --> 00:16:57,616
but it's a lava lake
180 kilometers across.

317
00:16:57,649 --> 00:17:00,352
So it's probably better
to call it a lava sea.

318
00:17:00,385 --> 00:17:04,223
It is Io's most persistent,
powerful volcano.

319
00:17:06,524 --> 00:17:07,759
And we think that it has

320
00:17:07,792 --> 00:17:11,530
a very unique way
of being resurfaced.

321
00:17:11,563 --> 00:17:14,032
We think that what is
happening at Loki Patera

322
00:17:14,065 --> 00:17:17,869
is that crust on the lava
lake forms with time,

323
00:17:17,902 --> 00:17:20,705
and it thickens with time
until it gets to a point

324
00:17:20,738 --> 00:17:23,909
where the crust starts to sink,

325
00:17:23,942 --> 00:17:28,113
and then basically the entire
surface of the lava lake

326
00:17:29,314 --> 00:17:32,284
is resurfaced by
this crust sinking

327
00:17:32,317 --> 00:17:37,189

and the sinking crust being
replaced with new lava.

328
00:17:37,222 --> 00:17:42,194
This is an analysis of a
single Galileo NIMS observation

329
00:17:42,227 --> 00:17:46,398
that was obtained in 2001,
and it shows a temperature map

330
00:17:49,100 --> 00:17:52,504
and age map of the surface
from the analysis of the data.

331
00:17:52,537 --> 00:17:56,708
And what this implies is
that this resurfacing wave,

332
00:17:58,209 --> 00:18:00,712
if you like, swept
around the Patera

333
00:18:00,745 --> 00:18:03,248
at a rate of about
a kilometer a day.

334
00:18:03,281 --> 00:18:07,018
So what happens is the
Patera resurfaces itself,

335
00:18:07,051 --> 00:18:08,920
and then it remains
quiescent for a while

336
00:18:08,953 --> 00:18:13,492
while the crust thickens, and
then the crust sinks again.

337
00:18:13,525 --> 00:18:17,696

And it's been doing this
periodically for decades.

338
00:18:21,900 --> 00:18:26,037
Well, in 2015, in 2015, the
Large Binocular Telescope

339
00:18:26,070 --> 00:18:30,108
Interferometer, which is on
a mountaintop in Arizona,

340
00:18:30,141 --> 00:18:33,979
collected this truly
astonishing set of observations

341
00:18:34,012 --> 00:18:36,782
which shows Europa
passing across

342
00:18:39,117 --> 00:18:42,387
and eclipsing or
occulting Loki Patera.

343
00:18:43,621 --> 00:18:45,991
So Loki Patera is here,

344
00:18:46,024 --> 00:18:50,028
and this is Europa passing
across in front of Io

345
00:18:51,196 --> 00:18:54,366
between Io and the
telescope on Earth.

346
00:18:57,735 --> 00:19:01,039
And what this means is
that as Europa's edge

347
00:19:01,072 --> 00:19:04,009
passes across Loki Patera,

348
00:19:04,042 --> 00:19:07,179
it covers up the Patera
in one direction,

349
00:19:07,212 --> 00:19:11,983
and we get this light curve
here as light is cut off

350
00:19:12,016 --> 00:19:13,818
and heat is cut off.

351
00:19:13,851 --> 00:19:16,755
But as Europa
uncovers Loki Patera,

352
00:19:18,856 --> 00:19:21,092
we get this curve with the limb

353
00:19:21,125 --> 00:19:22,661
going in a different direction.

354
00:19:22,694 --> 00:19:26,865
And so by fitting these little
squiggles in the dataset,

355
00:19:28,533 --> 00:19:32,370
we created, and this was an
effort led by Katherine de Kleer

356
00:19:32,403 --> 00:19:34,739
who's now at Caltech.

357
00:19:34,772 --> 00:19:38,810
We created the highest
spatial resolution map

358
00:19:38,843 --> 00:19:42,113
of Loki Patera's surface

that's ever been obtained,

359
00:19:42,146 --> 00:19:44,382
even including data
from spacecraft.

360
00:19:44,415 --> 00:19:49,221
We managed to create a map
over the entire Patera floor.

361
00:19:49,254 --> 00:19:52,123
And fitting this lava
lake model to it,

362
00:19:52,156 --> 00:19:55,393
looking at the distribution
of temperatures on the surface

363
00:19:55,426 --> 00:19:57,095
from which you can infer age,

364
00:19:57,128 --> 00:20:00,332
'cause the older the
surface, the cooler it is.

365
00:20:00,365 --> 00:20:02,267
The explanation
that we came up with

366
00:20:02,300 --> 00:20:06,471
for this particular temperature
distribution was this,

367
00:20:07,872 --> 00:20:11,843
two resurfacing waves
sweeping around the Patera

368
00:20:13,845 --> 00:20:16,114
to form this resulting
temperature distribution,

369
00:20:16,147 --> 00:20:17,549
which was observed

370
00:20:17,582 --> 00:20:20,118
by the Large Binocular
Telescope Interferometer.

371
00:20:20,151 --> 00:20:21,353
And this is something

372
00:20:21,386 --> 00:20:23,388
which is consistent with
previous observations.

373
00:20:23,421 --> 00:20:25,724
It's a really nice vindication

374
00:20:25,757 --> 00:20:28,760
of this lava lake
resurfacing model.

375
00:20:32,230 --> 00:20:35,634
A more active lava
lake on Io is at Pele,

376
00:20:37,602 --> 00:20:41,339
and Pele is at the center
of this bright red deposit,

377
00:20:41,372 --> 00:20:44,075
which is a plume
deposit, a plume fallout.

378
00:20:44,108 --> 00:20:45,710
It's a plume that's
hundreds of kilometers high,

379
00:20:45,743 --> 00:20:47,879

and it's led to this
deposit on the surface,

380
00:20:47,912 --> 00:20:51,016
rich in short-chain
sulfur allotropes

381
00:20:51,949 --> 00:20:54,353
about 1200 kilometers across.

382
00:20:55,787 --> 00:20:58,857
And we think that Pele has
every appearance of an active,

383
00:20:58,890 --> 00:21:03,428
over-turning lava lake
with the plume basically

384
00:21:03,461 --> 00:21:06,231
forcing its way up through
the middle of the lake

385
00:21:06,264 --> 00:21:09,368
and disrupting the
surface, yielding,

386
00:21:12,303 --> 00:21:14,973
revealing high temperature lava.

387
00:21:16,841 --> 00:21:18,843
And it's much larger, it's
about 38 kilometers across

388
00:21:18,876 --> 00:21:22,914
and much larger than its
terrestrial equivalents.

389
00:21:22,947 --> 00:21:26,918
This is the Kupaianaha
lava lake in Hawaii.

390
00:21:26,951 --> 00:21:28,420
Terrestrially, lava lakes

391
00:21:28,453 --> 00:21:32,491
are maybe 10 or 20 up to 100
or 200 meters in diameter.

392
00:21:34,959 --> 00:21:38,129
Io's volcanoes, Io's lava
lakes seem to be hundreds

393
00:21:38,162 --> 00:21:42,334
or even thousands of kilometers,
square kilometers in size.

394
00:21:43,801 --> 00:21:47,172
Loki Patera itself, Loki
Patera has a surface area

395
00:21:47,205 --> 00:21:49,708
of over 21,000
square kilometers,

396
00:21:49,741 --> 00:21:54,179
which makes it even
larger than West Virginia.

397
00:21:54,212 --> 00:21:58,450
Io's most powerful
eruptions, thermal outbursts,

398
00:21:58,483 --> 00:22:02,354
are now known to be caused
by large lava fountains

399
00:22:02,387 --> 00:22:05,690
gushing forth from
long fissures.

400
00:22:05,723 --> 00:22:07,859
And these sort of events
were actually seen,

401
00:22:07,892 --> 00:22:10,495
a couple of them
were seen by Galileo.

402
00:22:10,528 --> 00:22:13,932
This is what's happening
along this fissure here,

403
00:22:13,965 --> 00:22:15,967
and this is the
result of saturation.

404
00:22:16,000 --> 00:22:20,172
Because so much energy was being
received by the spacecraft,

405
00:22:21,038 --> 00:22:22,640
the detector saturated.

406
00:22:22,673 --> 00:22:23,942
And this is a problem

407
00:22:23,975 --> 00:22:25,977
that we've come across
time and time again

408
00:22:26,010 --> 00:22:30,015
with trying to image these
very powerful events.

409
00:22:31,382 --> 00:22:33,952
We now see these things
from Earth-based telescopes.

410
00:22:33,985 --> 00:22:36,087

They were actually discovered
by Earth-based telescopes

411
00:22:36,120 --> 00:22:37,989
back in the 1990s.

412
00:22:38,022 --> 00:22:40,325
But we're continuing
to discover these.

413
00:22:40,358 --> 00:22:43,595
They're quite rare, and
they're quite short-lived,

414
00:22:43,628 --> 00:22:44,829
but they're very powerful.

415
00:22:44,862 --> 00:22:47,832
In 2013, we saw two
of these at Rarog

416
00:22:47,865 --> 00:22:52,103
and Heno Patera in the
southern hemisphere of Io.

417
00:22:52,136 --> 00:22:53,772
This is an interesting image,

418
00:22:53,805 --> 00:22:56,241
because it does show that
that's short wavelengths,

419
00:22:56,274 --> 00:22:59,077
that Loki Patera does
not emit a lot of energy.

420
00:22:59,110 --> 00:23:02,046
Most of the energy
being emitted from Loki

421
00:23:02,079 --> 00:23:03,548
is at longer wavelengths.

422
00:23:03,581 --> 00:23:06,384
And what that tells us is
that generally speaking,

423
00:23:06,417 --> 00:23:09,154
Loki is a relatively
cool surface

424
00:23:10,321 --> 00:23:13,558
compared with what we
see at these outbursts.

425
00:23:13,591 --> 00:23:16,294
So for the purposes
of determining

426
00:23:16,327 --> 00:23:18,663
eruption temperature
of the lava,

427
00:23:18,696 --> 00:23:21,332
Loki Patera may not
be our best candidate,

428
00:23:21,365 --> 00:23:22,901
whereas something like Pele,

429
00:23:22,934 --> 00:23:25,403
where we have
overturning lava lakes,

430
00:23:25,436 --> 00:23:28,506
an overturning lava lake on
a much shorter time scale

431
00:23:28,539 --> 00:23:31,142

is a better candidate.

432
00:23:31,175 --> 00:23:32,811
So by looking at
all of this data

433
00:23:32,844 --> 00:23:36,047
and doing a lot of
modeling, we come up with,

434
00:23:36,080 --> 00:23:38,416
we've come up with a
classification schema

435
00:23:38,449 --> 00:23:42,454
where we can identify the
characteristic thermal

436
00:23:43,921 --> 00:23:48,593
fingerprints of different
styles of volcanic activity.

437
00:23:48,626 --> 00:23:51,196
The most powerful eruptions
are these outburst eruptions,

438
00:23:51,229 --> 00:23:53,031
these large lava
fountain events.

439
00:23:53,064 --> 00:23:57,802
We have the Pele overturning
lava lake right here,

440
00:23:57,835 --> 00:23:59,204
and at the bottom,

441
00:23:59,237 --> 00:24:02,740
we have the small but
powerful lava tube skylights.

442
00:24:02,773 --> 00:24:05,410
These are small but
very high-temperature.

443
00:24:05,443 --> 00:24:08,847
I'll be talking more
about these later.

444
00:24:08,880 --> 00:24:11,216
So, Io is a fascinating body

445
00:24:13,985 --> 00:24:16,788
in terms of, it
was the first body

446
00:24:16,821 --> 00:24:21,259
where we really did see
active resurfacing processes.

447
00:24:21,292 --> 00:24:23,561
But the Voyager, Cassini,

448
00:24:23,594 --> 00:24:25,997
and Galileo missions have shown

449
00:24:26,030 --> 00:24:29,367
that there were many other
satellites in the solar system

450
00:24:29,400 --> 00:24:33,071
which have this dynamic,
evolving structure.

451
00:24:35,840 --> 00:24:37,542
For example, we have Enceladus,

452
00:24:37,575 --> 00:24:40,578
which is one of the

moons of Saturn,

453
00:24:40,611 --> 00:24:42,247
which has water plumes erupting

454
00:24:42,280 --> 00:24:45,416
from the south polar
region, and we have Titan

455
00:24:45,449 --> 00:24:48,119
and the Jovian satellite Europa,

456
00:24:49,220 --> 00:24:52,156
which have geologically
young surfaces.

457
00:24:52,189 --> 00:24:55,193
But Io and all of
these bodies are,

458
00:24:55,226 --> 00:24:56,761
to some extent, tidally heated.

459
00:24:56,794 --> 00:25:01,766
But Io is the most tidally
heated body in the solar system,

460
00:25:01,799 --> 00:25:04,302
and it's probably the
best place to study

461
00:25:04,335 --> 00:25:07,339
this extreme limits
of this process.

462
00:25:09,407 --> 00:25:12,010
So the big picture as it
stands is that we know

463

00:25:12,043 --> 00:25:15,881
that Io and Europa are
tidally bound together,

464
00:25:18,482 --> 00:25:19,617
but how much heating,

465
00:25:19,650 --> 00:25:21,386
and where this heating
is taking place

466
00:25:21,419 --> 00:25:24,689
within the satellite is not
really well constrained.

467
00:25:24,722 --> 00:25:27,659
But as tidal heating is
most pronounced at Io,

468
00:25:27,692 --> 00:25:30,695
it's really knowing
Io's interior condition

469
00:25:30,728 --> 00:25:34,599
that gives us some insight
into further constraining

470
00:25:34,632 --> 00:25:37,902
how much heat is being
input into Europa.

471
00:25:37,935 --> 00:25:42,107
So, on Io, it's the eruption
temperature of Io's lavas

472
00:25:43,541 --> 00:25:46,778
which could be diagnostic
of interior conditions.

473
00:25:46,811 --> 00:25:49,781

And so, looking to Io's
volcanoes to get this data

474
00:25:49,814 --> 00:25:51,249
is what we need to do

475
00:25:51,282 --> 00:25:55,153
as a way of constraining
the interior state of Io.

476
00:25:56,587 --> 00:25:58,790
So the big question in the
wake of the Galileo mission

477
00:25:58,823 --> 00:26:00,291
regarding volcanism and Io

478
00:26:00,324 --> 00:26:04,262
is what is the composition
of the silicate lavas on Io?

479
00:26:04,295 --> 00:26:07,098
This reflects what's
happening inside.

480
00:26:07,131 --> 00:26:08,566
We know that Io's
volcanism is dominated

481
00:26:08,599 --> 00:26:12,604
by low-viscosity, quite
fluid lava, like basalt.

482
00:26:14,305 --> 00:26:17,642
Basalt erupts at about
1140 centrigrade,

483
00:26:19,243 --> 00:26:21,512
and this is the most common

484
00:26:21,545 --> 00:26:24,749
volcanic material
in the solar system.

485
00:26:24,782 --> 00:26:27,652
But it's also possible
that with Io, on Io,

486
00:26:27,685 --> 00:26:31,589
that we have a type of lava
called ultramafic lava,

487
00:26:31,622 --> 00:26:33,959
one of which is a Komatiite.

488
00:26:34,959 --> 00:26:36,361
And this erupts

489
00:26:36,394 --> 00:26:39,631
at hundreds of centigrade
higher temperatures.

490
00:26:41,332 --> 00:26:45,503
And this is interesting to
us because ultramafic lavas

491
00:26:46,971 --> 00:26:50,108
were once common on Earth
in Earth's distance past,

492
00:26:50,141 --> 00:26:52,243
and it might have been a time

493
00:26:52,276 --> 00:26:56,348
when this reflected a
hotter mantel in the earth.

494
00:26:57,715 --> 00:27:01,352
So if ultramafic lavas

are indeed erupting on Io,

495
00:27:01,385 --> 00:27:02,854
Io would truly be

496
00:27:04,321 --> 00:27:07,892
a window back into
Earth's geological past.

497
00:27:09,360 --> 00:27:11,829
Now, the hotter the lava,
the more interior heating

498
00:27:11,862 --> 00:27:15,099
is taking place, and the
more liquid the interior.

499
00:27:15,132 --> 00:27:18,136
But it's very difficult
to tell the difference

500
00:27:18,169 --> 00:27:22,507
between ultramafic and basaltic
lavas by temperature alone.

501
00:27:22,540 --> 00:27:24,008
Firstly, you have to look

502
00:27:24,041 --> 00:27:27,011
at a very narrow part of the
thermal emission spectrum,

503
00:27:27,044 --> 00:27:30,815
and secondly, the problem
here, and this is something

504
00:27:30,848 --> 00:27:35,153
that has bedeviled efforts to
do this with remote sensing

505
00:27:35,186 --> 00:27:37,622
is that we're trying
to tell the difference

506
00:27:37,655 --> 00:27:40,525
between a lava that erupts
at a very high temperature

507
00:27:40,558 --> 00:27:44,228
and something that erupts at
a very, very high temperature.

508
00:27:44,261 --> 00:27:47,098
So, Komatiite, it really
takes a couple of seconds

509
00:27:47,131 --> 00:27:51,302
for a Komatiite erupting at
this temperature of, say,

510
00:27:52,603 --> 00:27:55,840
1850 Kelvin to cool
down to the temperature

511
00:27:55,873 --> 00:27:57,975
at which basalt erupts.

512
00:27:58,008 --> 00:28:00,678
And so it's very
difficult to tell

513
00:28:00,711 --> 00:28:03,581
one from the other, and if
you're going to go to Io

514
00:28:03,614 --> 00:28:06,517
and look at styles
of volcanic activity

515

00:28:06,550 --> 00:28:07,985
to try and do this,

516
00:28:08,018 --> 00:28:11,923
only certain styles of
volcanic activity will do.

517
00:28:11,956 --> 00:28:14,625
And the first is lava fountains.

518
00:28:14,658 --> 00:28:16,294
And this is something we
have to get pretty close to

519
00:28:16,327 --> 00:28:18,863
and image, say, the
base of a lava fountain

520
00:28:18,896 --> 00:28:23,201
before the lava that's
gushing out of the ground

521
00:28:23,234 --> 00:28:24,736
can cool too much.

522
00:28:26,604 --> 00:28:28,072
And the problem with this

523
00:28:28,105 --> 00:28:30,141
is that these are relatively
rare, and it's impossible

524
00:28:30,174 --> 00:28:33,311
to predict where these
are going to happen.

525
00:28:33,344 --> 00:28:37,549
Lava tube skylights are a
particularly good candidate

526
00:28:38,816 --> 00:28:42,320
for doing this,
because they're small,

527
00:28:42,353 --> 00:28:45,790
you have a very high
temperature gradient

528
00:28:47,191 --> 00:28:51,028
between the lava tube skylight
and the surrounding area,

529
00:28:51,061 --> 00:28:52,630
so these things
stick out very well,

530
00:28:52,663 --> 00:28:54,932
and the temperatures inside

531
00:28:54,965 --> 00:28:57,635
are very close to
eruption temperature

532
00:28:57,668 --> 00:29:02,273
because the lava tube
itself is highly insulating.

533
00:29:02,306 --> 00:29:04,342
And then we have
lava, lava lakes.

534
00:29:04,375 --> 00:29:07,378
And what we're interesting
about in lava lakes

535
00:29:07,411 --> 00:29:10,448
is the fountaining
that takes place,

536

00:29:10,481 --> 00:29:12,016
because it's the
fountaining events

537
00:29:12,049 --> 00:29:16,121
that reveal the lava at
its highest temperatures.

538
00:29:17,521 --> 00:29:20,358
So, I've been traveling around
and looking at lava lakes

539
00:29:20,391 --> 00:29:23,494
and taking models
of volcanic activity

540
00:29:23,527 --> 00:29:27,665
to understand how
best to measure

541
00:29:27,698 --> 00:29:29,066
lava eruption
temperature.

542
00:29:29,099 --> 00:29:32,904
So, a few years ago, I went
to Erebus in Antarctica.

543
00:29:34,505 --> 00:29:37,141
This is, these are
observations obtained

544
00:29:37,174 --> 00:29:41,246
by a satellite in Earth
orbit, Earth Observing-1,

545
00:29:42,179 --> 00:29:45,183
and this is a visible image,

546
00:29:45,216 --> 00:29:46,851

and this is an infrared image.

547
00:29:46,884 --> 00:29:49,120
And we can see the lava lake
here with a smaller pit.

548
00:29:49,153 --> 00:29:52,657
And I'm actually standing
in a pixel about here

549
00:29:52,690 --> 00:29:54,192
as this was taken.

550
00:29:56,460 --> 00:30:00,632
And here I am at about
13,000 feet on Mount Erebus,

551
00:30:03,767 --> 00:30:06,871
and it's a bright,
sunny, summer day,

552
00:30:06,904 --> 00:30:09,640
and the temperature,
the ambient temperature

553
00:30:09,673 --> 00:30:13,678
without wind chill is
about -40 centigrade.

554
00:30:13,711 --> 00:30:16,047
And at the summit...

555
00:30:16,080 --> 00:30:17,548
Oh, this is our camp.

556
00:30:17,581 --> 00:30:19,817
This is at about 11,000 feet.

557
00:30:19,850 --> 00:30:22,587

This is the summit of Erebus.

558
00:30:22,620 --> 00:30:27,525
At the summit, there's a
crater about 600 meters across,

559
00:30:27,558 --> 00:30:30,328
and it's about 250 meters deep.

560
00:30:30,361 --> 00:30:34,165
And in that crater there
is an active lava lake

561
00:30:34,198 --> 00:30:36,434
of a lava called phonolite.

562
00:30:37,568 --> 00:30:40,271
It's quite a rare composition.

563
00:30:40,304 --> 00:30:41,906
And this is the
lava lake itself.

564
00:30:41,939 --> 00:30:45,276
It's about 38 meters
across, and one of the most

565
00:30:45,309 --> 00:30:48,313
extraordinary things
I've ever seen.

566
00:30:50,381 --> 00:30:52,717
And I took down
a thermal imager,

567
00:30:52,750 --> 00:30:56,087
a FLIR thermal imager
with me, and this,

568

00:30:57,554 --> 00:31:01,325
this is the data, some of
the data that was collected.

569
00:31:01,358 --> 00:31:04,996
And what we see here is
that lava is welling up

570
00:31:05,029 --> 00:31:07,164
at the center of the lake,

571
00:31:07,197 --> 00:31:10,234
forming a crust, which
then moves laterally,

572
00:31:10,267 --> 00:31:14,038
and then the lava goes
down at the edges.

573
00:31:14,071 --> 00:31:16,307
And this has been circulating
around between the surface

574
00:31:16,340 --> 00:31:18,776
and the deep-seated
magma chamber,

575
00:31:18,809 --> 00:31:22,513
about three or four
kilometers down.

576
00:31:22,546 --> 00:31:26,617
So, this was a great test
of a model that was created

577
00:31:26,650 --> 00:31:31,188
to determine the temperature
and area distribution.

578
00:31:31,221 --> 00:31:33,157

This is just a
cartoon of that model.

579
00:31:33,190 --> 00:31:37,628
We have lava rising up,
spreading and then sinking.

580
00:31:37,661 --> 00:31:41,232
So there is a
mathematically-defined

581
00:31:41,265 --> 00:31:44,602
progression in cooling across
the surface of the lake.

582
00:31:44,635 --> 00:31:46,470
And if you integrate over that,

583
00:31:46,503 --> 00:31:48,973
and then you can compare
that with the data,

584
00:31:49,006 --> 00:31:50,174
this is what we got.

585
00:31:50,207 --> 00:31:53,511
And this was a
great pleasure to me

586
00:31:53,544 --> 00:31:57,715
to actually do this, because
the model fit to the data.

587
00:31:58,549 --> 00:32:00,351
We produced the thermal emission

588
00:32:00,384 --> 00:32:03,487
as a function of wavelength,
the total power emitted,

589
00:32:03,520 --> 00:32:06,958
and the area of the lava lake
just down to a few percent.

590
00:32:06,991 --> 00:32:09,193
So this is very gratifying.

591
00:32:09,226 --> 00:32:11,829
There was a slight
discrepancy in the fit

592
00:32:11,862 --> 00:32:13,497
between the model down here,

593
00:32:13,530 --> 00:32:14,732
and that is just basically

594
00:32:14,765 --> 00:32:19,236
because the model used
a basaltic composition,

595
00:32:19,269 --> 00:32:21,405
and it was only the lava
eruption temperature

596
00:32:21,438 --> 00:32:22,606
that was different.

597
00:32:22,639 --> 00:32:24,208
And that's why there's
a slight gap here.

598
00:32:24,241 --> 00:32:26,911
So it looks like the model
is actually very sensitive

599
00:32:26,944 --> 00:32:30,614
to temperature, and this
improves our confidence

600
00:32:30,647 --> 00:32:34,652
of fitting data that we
get from the spacecraft.

601
00:32:36,553 --> 00:32:39,891
Now, the resurfacing
mechanism at Erebus

602
00:32:43,193 --> 00:32:45,696
was generally very quiescent,

603
00:32:45,729 --> 00:32:49,901
but when I was there in 2005,
every six to nine hours,

604
00:32:51,335 --> 00:32:55,273
the lava lake would
resurface itself like this.

605
00:33:00,110 --> 00:33:03,681
[Ashley mimics explosion]

606
00:33:06,750 --> 00:33:09,587
[audience laughs]

607
00:33:10,821 --> 00:33:13,791
I have to do my own
special effects.

608
00:33:13,824 --> 00:33:14,959
But that's what it sounded like.

609
00:33:14,992 --> 00:33:16,193
[audience applauds]

610
00:33:16,226 --> 00:33:18,429
It was pretty impressive
when this thing blew.

611
00:33:18,462 --> 00:33:20,798
So, yeah, this is a
Strombolian eruption,

612
00:33:20,831 --> 00:33:23,067
and it basically
throws out lava bombs

613
00:33:23,100 --> 00:33:26,104
up to three-quarters
of a kilometer.

614
00:33:28,539 --> 00:33:29,707
So, you gotta be careful.

615
00:33:29,740 --> 00:33:32,577
[audience laughs]

616
00:33:34,578 --> 00:33:37,481
Okay, all the bad acting aside,

617
00:33:37,514 --> 00:33:41,118
the guy under the rock,
his name's Alexander Gurst.

618
00:33:41,151 --> 00:33:44,889
And at the time, he
was a graduate student

619
00:33:44,922 --> 00:33:46,824
at the University of Hamburg,

620
00:33:46,857 --> 00:33:49,027
and now, he's an astronaut

621
00:33:50,294 --> 00:33:53,030
in the European Space
Agency Astronaut Corps,

622
00:33:53,063 --> 00:33:54,331
and he's already spent one tour

623
00:33:54,364 --> 00:33:55,666
on the International
Space Station,

624
00:33:55,699 --> 00:33:58,202
and he's mission
commander on a mission

625
00:33:58,235 --> 00:34:01,472
that's going to be
launched in 2018.

626
00:34:01,505 --> 00:34:03,774
Well done, Alexander.

627
00:34:03,807 --> 00:34:07,545
So, the results from
the field trip to Erebus

628
00:34:08,812 --> 00:34:10,147
and all the data analysis

629
00:34:10,180 --> 00:34:13,317
is that we see that lava
lake thermal signatures,

630
00:34:13,350 --> 00:34:16,087
the characteristic
thermal signature

631
00:34:16,120 --> 00:34:17,488
of a lava
lake on Earth

632
00:34:17,521 --> 00:34:21,692

and its contemporaries on Io
are actually pretty similar.

633
00:34:22,893 --> 00:34:24,995
The model fits used to
interpret the Io data,

634
00:34:25,028 --> 00:34:27,431
the model was actually
developed to interpret Io data

635
00:34:27,464 --> 00:34:29,967
actually works really
well on terrestrial data.

636
00:34:30,000 --> 00:34:31,836
So that's a good test.

637
00:34:32,936 --> 00:34:35,172
And the analysis
appears to be sensitive

638
00:34:35,205 --> 00:34:37,842
to eruption temperatures,
which is important.

639
00:34:37,875 --> 00:34:40,678
This is all very well
to Erebus, but things,

640
00:34:40,711 --> 00:34:44,982
how do things like with
a better analog for Io?

641
00:34:45,015 --> 00:34:49,086
And so a few years later,
actually, I was asked

642
00:34:49,119 --> 00:34:53,424
to go out to this volcano in

Africa, the Erta Ale volcano

643
00:34:53,457 --> 00:34:57,628
in the Danakil Depression in
the Afar region of Ethiopia

644
00:34:59,229 --> 00:35:01,232
by the BBC, who are
filming a series

645
00:35:01,265 --> 00:35:03,501
called Wonders of
the Solar System.

646
00:35:03,534 --> 00:35:05,970
Io is obviously a wonder
of the solar system,

647
00:35:06,003 --> 00:35:09,707
and so they wanted to talk
to me about it out there.

648
00:35:09,740 --> 00:35:12,209
I jumped at the chance.

649
00:35:12,242 --> 00:35:15,446
Erta Ale is located
at the northern end

650
00:35:15,479 --> 00:35:17,581
of the East African rift system.

651
00:35:17,614 --> 00:35:20,651
This is where Africa is
pulling itself apart,

652
00:35:20,684 --> 00:35:23,287
and it's a basalt lava lake.

653

00:35:23,320 --> 00:35:24,555
And here it is.

654
00:35:25,689 --> 00:35:28,759
In 2009, it was about
55 meters across.

655
00:35:30,260 --> 00:35:32,930
There was a lot of vigorous
churning around at the edges

656
00:35:32,963 --> 00:35:35,232
and the occasional lava
fountain in the middle,

657
00:35:35,265 --> 00:35:37,001
and it's one of the most
extraordinary things

658
00:35:37,034 --> 00:35:38,703
that I've ever seen.

659
00:35:40,070 --> 00:35:41,605
And so here I am on the summit

660
00:35:41,638 --> 00:35:45,309
of Erta Ale on a bright,
sunny, summer day,

661
00:35:45,342 --> 00:35:49,180
and the ambient temperature
is 133 Fahrenheit.

662
00:35:50,080 --> 00:35:51,849
It's 56 centigrade.

663
00:35:51,882 --> 00:35:55,686
Sorts of it's not surprising
I look a little pink.

664
00:35:55,719 --> 00:35:56,921
Again, with a thermal imager.

665
00:35:56,954 --> 00:35:58,589
These lava lake tend
to be in these really,

666
00:35:58,622 --> 00:36:01,358
you know, extreme environments.

667
00:36:01,391 --> 00:36:03,994
Here I am again with
another thermal imager.

668
00:36:04,027 --> 00:36:08,032
And this is an hour in
the life of the lava lake

669
00:36:10,334 --> 00:36:13,904
compressed down into about
10 seconds of time lapse.

670
00:36:13,937 --> 00:36:18,109
And what I'd like to point
out is a small lava fountain

671
00:36:19,776 --> 00:36:21,679
just about here.

672
00:36:21,712 --> 00:36:23,447
There it goes.

673
00:36:23,480 --> 00:36:26,750
This is where the crust
has been disrupted,

674
00:36:26,783 --> 00:36:29,887
and areas of very high
temperature are being revealed.

675
00:36:29,920 --> 00:36:31,622
And that's what
we're interested in.

676
00:36:31,655 --> 00:36:36,126
So, I took a look at
these data to determine

677
00:36:36,159 --> 00:36:39,063
what the effect would
be of any kind of delay

678
00:36:39,096 --> 00:36:42,866
getting data at
different wavelengths.

679
00:36:42,899 --> 00:36:46,670
A traditional way for
spacecraft, like the Voyager,

680
00:36:46,703 --> 00:36:49,373
spacecraft images to work is,

681
00:36:49,406 --> 00:36:51,275
you take an image of the surface

682
00:36:51,308 --> 00:36:53,310
through one filter.

683
00:36:53,343 --> 00:36:54,578
You move a filter wheel.

684
00:36:54,611 --> 00:36:57,081
You take another image,
do another filter wheel.

685
00:36:57,114 --> 00:36:58,282
After another

filter on the wheel,

686
00:36:58,315 --> 00:37:00,117
you move the filter again.

687
00:37:00,150 --> 00:37:01,318
You take another image.

688
00:37:01,351 --> 00:37:03,254
Then you combine
those images together,

689
00:37:03,287 --> 00:37:05,322
and you get a color image.

690
00:37:05,355 --> 00:37:07,758
That's fine for
planetary surfaces,

691
00:37:07,791 --> 00:37:10,427
but where we have something
that is changing rapidly,

692
00:37:10,460 --> 00:37:12,796
because it's actually
cooling very fast,

693
00:37:12,829 --> 00:37:14,164
what is the effect of that

694
00:37:14,197 --> 00:37:17,301
when you try this
experiment again?

695
00:37:17,334 --> 00:37:19,203
And this is what we found,

696
00:37:19,236 --> 00:37:21,505
that with even a second delay

697
00:37:21,538 --> 00:37:24,208
in taking data at
different wavelengths,

698
00:37:24,241 --> 00:37:26,277
we got these massive...

699
00:37:26,310 --> 00:37:27,511
Here we go.

700
00:37:27,544 --> 00:37:30,447
These massive changes
in derived temperature,

701
00:37:30,480 --> 00:37:33,884
which really does make
it very difficult to have

702
00:37:33,917 --> 00:37:37,454
any confidence in an actual
temperature derivation.

703
00:37:37,487 --> 00:37:40,724
But when you cut the
difference in time

704
00:37:40,757 --> 00:37:43,361
down to a fraction of a second,

705
00:37:45,696 --> 00:37:49,533
we get a much smaller
amount of variation.

706
00:37:49,566 --> 00:37:53,337
Of course, this would be,
this would be a flat line

707
00:37:53,370 --> 00:37:57,474

if the data were
obtained simultaneously.

708
00:37:57,507 --> 00:38:02,379
So, what we found from Erta
Ale is that temperatures,

709
00:38:02,412 --> 00:38:06,684
that areas of target
temperatures change so rapidly

710
00:38:06,717 --> 00:38:10,020
that observations have
to be obtained very fast,

711
00:38:10,053 --> 00:38:13,724
or ideally, simultaneously
at different wavelengths.

712
00:38:13,757 --> 00:38:16,293
Now, with Galileo data, we
tried deriving temperatures

713
00:38:16,326 --> 00:38:21,031
from Galileo data by
combining different SSI frames

714
00:38:21,064 --> 00:38:24,702
and combining NIMS
data with SSI data,

715
00:38:24,735 --> 00:38:27,104
and we found that with
seconds and minutes

716
00:38:27,137 --> 00:38:28,472
between observations,

717
00:38:28,505 --> 00:38:31,842
it damages our confidence

in the results,

718
00:38:31,875 --> 00:38:33,744
because the target
that we're looking at

719
00:38:33,777 --> 00:38:36,146
was probably changing
in that time.

720
00:38:36,179 --> 00:38:39,183
Now, this is not a
criticism of Galileo

721
00:38:39,216 --> 00:38:41,018
by any means of the imagination,

722
00:38:41,051 --> 00:38:44,755
because the instruments of
Galileo were simply not designed

723
00:38:44,788 --> 00:38:48,926
to do what we'd like to
do with the next mission.

724
00:38:48,959 --> 00:38:50,728
We see as far as we do

725
00:38:50,761 --> 00:38:53,397
because we stand on the
shoulders of giants.

726
00:38:53,430 --> 00:38:56,867
So, this is not a criticism
of Galileo at all.

727
00:38:56,900 --> 00:38:59,036
The upshot of this
is that observations

728
00:38:59,069 --> 00:39:02,706
have to be obtained in
a fraction of a second.

729
00:39:02,739 --> 00:39:04,742
So, we're really
getting close now

730
00:39:04,775 --> 00:39:08,946
to what we need to
overcome these problems.

731
00:39:08,979 --> 00:39:11,081
We have a very good handle

732
00:39:11,114 --> 00:39:15,286
on the derivation of the
style of volcanic activity

733
00:39:16,653 --> 00:39:18,555
from studying volcanoes on Earth

734
00:39:18,588 --> 00:39:21,025
and studying volcanoes on Io.

735
00:39:24,895 --> 00:39:28,532
On that note, there was a
paper published just last year

736
00:39:28,565 --> 00:39:31,935
where we quantified
the thermal emission

737
00:39:31,968 --> 00:39:34,972
that you would get from
a lava tube skylight

738
00:39:35,005 --> 00:39:39,376
for both basalt and

ultramafic compositions.

739
00:39:39,409 --> 00:39:43,847
So now we have the distinctive
thermal fingerprints

740
00:39:43,880 --> 00:39:48,052
for both of these compositions
to help us analyze any

741
00:39:49,453 --> 00:39:53,257
new spacecraft data that we
might get on volcanism on Io,

742
00:39:53,290 --> 00:39:56,193
or the style of volcanism on Io.

743
00:39:56,226 --> 00:40:00,398
We have a very good handle on
the rapid cooling of new lava.

744
00:40:01,331 --> 00:40:02,766
We know how the process works,

745
00:40:02,799 --> 00:40:05,302
and we know some of the problems

746
00:40:05,335 --> 00:40:08,038
that have to be
overcome with that.

747
00:40:08,071 --> 00:40:10,207
And with lava fountains

748
00:40:10,240 --> 00:40:13,410
and with fountaining
in lava lakes,

749
00:40:13,443 --> 00:40:14,845

there is still the problem

750
00:40:14,878 --> 00:40:19,049
of the unpredictable
magnitude of thermal emission.

751
00:40:19,082 --> 00:40:23,254
Because if too much radiance
is captured by the detector,

752
00:40:24,688 --> 00:40:27,357
it will saturate, and
then the data are no good

753
00:40:27,390 --> 00:40:30,360
for deriving
eruption temperature.

754
00:40:30,393 --> 00:40:31,962
But there's a number
of ways of doing it,

755
00:40:31,995 --> 00:40:33,497
and here's one.

756
00:40:33,530 --> 00:40:37,501
This is an effort being led
by Alex Soibel here at JPL.

757
00:40:39,503 --> 00:40:43,073
It uses something called
a HOT-BIRD detector,

758
00:40:43,106 --> 00:40:45,976
which was invented here at JPL,

759
00:40:46,009 --> 00:40:47,845
and an integrated circuit

760

00:40:47,878 --> 00:40:50,681
that was invented
at MIT Lincoln Labs.

761
00:40:50,714 --> 00:40:53,050
And it splits the
signal coming in.

762
00:40:53,083 --> 00:40:57,721
It obtains data simultaneously
at multiple wavelengths.

763
00:40:57,754 --> 00:41:00,190
For our purposes, the
detector and the circuit

764
00:41:00,223 --> 00:41:03,427
are non-saturating, so
there's no saturation effect,

765
00:41:03,460 --> 00:41:05,496
and it's got a fast
integration time.

766
00:41:05,529 --> 00:41:07,898
So this is just one
approach that can be used

767
00:41:07,931 --> 00:41:09,933
to get the data that we need

768
00:41:09,966 --> 00:41:14,138
to measure lava eruption
temperatures on Io accurately.

769
00:41:15,572 --> 00:41:19,409
So, now, we really do have all
of the pieces of the puzzle.

770
00:41:19,442 --> 00:41:22,112

We can identify different
eruption styles on Io.

771
00:41:22,145 --> 00:41:23,881
We can understand...

772
00:41:23,914 --> 00:41:26,250
We have a good
understanding of how these

773
00:41:26,283 --> 00:41:29,520
different eruptions behave
thermally and temporally.

774
00:41:29,553 --> 00:41:32,055
So we really do know what
observations to make.

775
00:41:32,088 --> 00:41:34,424
We have some
designs

776
00:41:34,457 --> 00:41:35,659
for instruments that
collect the data,

777
00:41:35,692 --> 00:41:38,896
and we have models
that can be used

778
00:41:38,929 --> 00:41:40,831
to interpret the
data once obtained.

779
00:41:40,864 --> 00:41:45,502
And now the only thing we're
missing now are new data.

780
00:41:45,535 --> 00:41:48,805
So, the unlocking

of Io's secrets

781
00:41:48,838 --> 00:41:51,241
has been an incremental process.

782
00:41:51,274 --> 00:41:53,443
The Voyager
spacecraft discovered

783
00:41:53,476 --> 00:41:55,145
that Io was volcanically active,

784
00:41:55,178 --> 00:41:58,515
and we did so with instruments
that were not designed

785
00:41:58,548 --> 00:42:01,151
for looking at any kind
of silicate volcanism.

786
00:42:01,184 --> 00:42:02,719
This was completely unthought-of

787
00:42:02,752 --> 00:42:05,589
when the instruments were
designed in the first place.

788
00:42:05,622 --> 00:42:08,725
Galileo discovered
that silicate volcanism

789
00:42:08,758 --> 00:42:12,129
was the dominant from
of volcanism on Io,

790
00:42:12,162 --> 00:42:13,530
and now the question is,

791
00:42:13,563 --> 00:42:15,699

what is the actual
composition of the lavas?

792
00:42:15,732 --> 00:42:19,436
Is it uniform across Io, or are
there different compositions

793
00:42:19,469 --> 00:42:22,472
being erupted in
different places

794
00:42:22,505 --> 00:42:27,144
which reflect the depth
of origin of these lavas?

795
00:42:27,177 --> 00:42:30,514
Are they hot, or
are they very hot?

796
00:42:30,547 --> 00:42:33,584
So, really, a new mission
is needed to get back to Io,

797
00:42:33,617 --> 00:42:34,551
and there've been
different missions

798
00:42:34,584 --> 00:42:35,953
proposed over the years.

799
00:42:35,986 --> 00:42:38,355
This is one that was proposed
a couple of years ago.

800
00:42:38,388 --> 00:42:41,024
It may be proposed
again by Alfred McEwen

801
00:42:41,057 --> 00:42:43,494
at the University of Arizona.

802
00:42:44,628 --> 00:42:48,132
It was called the Io
Volcano Observer or IVO.

803
00:42:49,599 --> 00:42:53,170
IVO and other missions like
it would be the first mission

804
00:42:53,203 --> 00:42:56,473
sent back to Io dedicated
to study Io's volcanoes

805
00:42:56,506 --> 00:42:58,642
and the interior processes

806
00:42:58,675 --> 00:43:02,379
with instruments designed
specifically to overcome

807
00:43:02,412 --> 00:43:06,483
the problems, the
problems that are inherent

808
00:43:06,516 --> 00:43:08,685
in trying to understand
what's happening on Io,

809
00:43:08,718 --> 00:43:11,021
to finally nail down
eruption temperatures,

810
00:43:11,054 --> 00:43:13,056
constrain interior state,

811
00:43:13,089 --> 00:43:16,760
and then this can be
applied also to Europa.

812

00:43:17,727 --> 00:43:19,163
So in conclusion,

813
00:43:20,296 --> 00:43:22,799
we really truly are
living in a new,

814
00:43:22,832 --> 00:43:26,069
in a golden age of exploration.

815
00:43:26,102 --> 00:43:30,073
We know the big Io
questions can be answered,

816
00:43:30,106 --> 00:43:31,842
and to a volcanologist,

817
00:43:31,875 --> 00:43:34,911
Io is a truly amazing place.

818
00:43:34,944 --> 00:43:37,547
It's a window into Earth's past.

819
00:43:37,580 --> 00:43:41,418
It's key to understanding
Jupiter's satellites.

820
00:43:41,451 --> 00:43:43,987
It's a volcanologist's paradise.

821
00:43:44,020 --> 00:43:44,921
Thank you very much.

822
00:43:44,954 --> 00:43:47,958
[audience applauds]

823
00:43:55,565 --> 00:44:00,370
If anyone has any questions,
please use the microphone

824
00:44:00,403 --> 00:44:03,207
set up in the
middle of the room.

825
00:44:07,177 --> 00:44:08,512
>> Hi, great presentation.

826
00:44:08,545 --> 00:44:10,414
I had a quick
question with regards

827
00:44:10,447 --> 00:44:13,517
to potential for an
atmosphere on Io.

828
00:44:14,684 --> 00:44:16,787
Is there any indication
there was an atmosphere,

829
00:44:16,820 --> 00:44:18,689
or is there an atmosphere?

830
00:44:18,722 --> 00:44:21,158
Will there be an
atmosphere in the future?

831
00:44:21,191 --> 00:44:25,362
>> There is a very, very thin
atmosphere of sulfur dioxide

832
00:44:27,597 --> 00:44:31,101
which appears to
freeze out at night.

833
00:44:31,134 --> 00:44:33,503
It's not as thick as
Earth's atmosphere.

834

00:44:33,536 --> 00:44:36,907
We're talking about something
that is just a tiny fraction

835
00:44:36,940 --> 00:44:40,043
of a bar, and it's
basically sulfur dioxide

836
00:44:40,076 --> 00:44:44,648
that's generated from
the volcanoes themselves

837
00:44:44,681 --> 00:44:47,084
by lava flow across the surface

838
00:44:47,117 --> 00:44:51,288
and melting and remobilizing
sulfur dioxide gas and sulfur

839
00:44:56,259 --> 00:44:58,261
on the surface.

840
00:44:58,294 --> 00:45:00,164
It's remobilizing ices.

841
00:45:03,199 --> 00:45:04,668
>> Hi, I'm just wondering
if you have any plans

842
00:45:04,701 --> 00:45:06,636
to visit more volcanoes,

843
00:45:06,669 --> 00:45:09,372
or if there's any specific
ones you'd like to go to?

844
00:45:09,405 --> 00:45:12,242
>> I try to visit as
many volcanoes as I can.

845
00:45:12,275 --> 00:45:14,711
I made my first trip
to Etna this year,

846
00:45:14,744 --> 00:45:16,647
which is very exciting.

847
00:45:17,947 --> 00:45:21,718
That's where I encountered
sort of the mantra

848
00:45:21,751 --> 00:45:24,554
of the volcanologist, which was,

849
00:45:24,587 --> 00:45:26,723
you should have stayed
an extra couple of days.

850
00:45:26,756 --> 00:45:28,959
Usually, it's you should
have been here last week.

851
00:45:28,992 --> 00:45:30,660
In this case, I left
a couple of days

852
00:45:30,693 --> 00:45:33,530
before it erupted
quite spectacularly.

853
00:45:33,563 --> 00:45:36,299
I would like to go
back to Erta Ale

854
00:45:36,332 --> 00:45:37,935
with new equipment.

855
00:45:38,868 --> 00:45:41,304
I spend a lot of

time at Kilauea,

856
00:45:41,337 --> 00:45:44,441
'cause Kilauea is convenient,
it's relatively close,

857
00:45:44,474 --> 00:45:46,810
and it's a great analog
for a lot of the styles

858
00:45:46,843 --> 00:45:49,112
of volcanic activity
that we see on Io.

859
00:45:49,145 --> 00:45:50,680
So it's a great test bed,

860
00:45:50,713 --> 00:45:52,783
and it's a great learning
experience to go out and watch

861
00:45:52,816 --> 00:45:55,352
the eruptions take place.

862
00:45:55,385 --> 00:45:56,220
Yeah.

863
00:45:58,421 --> 00:45:59,890
>> Hi.

864
00:45:59,923 --> 00:46:03,527
I understand there are about
400 active volcanoes on Io

865
00:46:05,195 --> 00:46:09,866
contributing to the ejecta
and the plasma torus.

866
00:46:09,899 --> 00:46:14,071

And my question is, are there
any dormant volcanoes on Io

867
00:46:15,305 --> 00:46:19,042
or do you know of any
that are going dormant?

868
00:46:20,143 --> 00:46:22,746
>> We've identified
250 locations

869
00:46:26,316 --> 00:46:30,154
where there's been active
or recent volcanism,

870
00:46:31,588 --> 00:46:34,491
and there are, as you
quite correctly say,

871
00:46:34,524 --> 00:46:38,695
there are about 400 sites on
Io which look like dormant...

872
00:46:41,364 --> 00:46:43,934
There are 400 sites on Io which

873
00:46:45,602 --> 00:46:48,405
have the appearance
of past activity

874
00:46:48,438 --> 00:46:51,208
as well as the current activity.

875
00:46:51,241 --> 00:46:54,177
So yes, there are
many sites on Io

876
00:46:54,210 --> 00:46:56,479
which look as if they
once were volcanic,

877
00:46:56,512 --> 00:46:59,382
but don't appear
to be volcanic now.

878
00:46:59,415 --> 00:47:03,220
I don't think that there's
been any correlation

879
00:47:03,253 --> 00:47:05,822
between where the activity
is taking place now

880
00:47:05,855 --> 00:47:10,227
and where it seemed to have
taken place at some other time.

881
00:47:10,260 --> 00:47:13,530
So there may be something
hidden in those data

882
00:47:13,563 --> 00:47:18,368
which reflect a shift in
maybe regional volcanism,

883
00:47:18,401 --> 00:47:20,637
but no, I can't say
anything definitive

884
00:47:20,670 --> 00:47:22,873
about that right now.

885
00:47:22,906 --> 00:47:24,107
>> Thank you.

886
00:47:24,140 --> 00:47:25,308
>> Yeah.

887
00:47:25,341 --> 00:47:26,577

You're welcome.

888
00:47:28,244 --> 00:47:29,446
>> So, first of all,

889
00:47:29,479 --> 00:47:31,248
thank you very much
for your presentation.

890
00:47:31,281 --> 00:47:33,083
It's been very eye-opening.

891
00:47:33,116 --> 00:47:35,752
[audience laughs]

892
00:47:35,785 --> 00:47:38,121
Pun not intended, I promise.

893
00:47:40,323 --> 00:47:43,260
So my question is,
have we been able

894
00:47:43,293 --> 00:47:47,731
to detect a magnetic field
around Io, and if not,

895
00:47:47,764 --> 00:47:50,767
what's the theory
for what's missing

896
00:47:51,935 --> 00:47:55,138
in development for
that magnetic field?

897
00:47:57,941 --> 00:48:00,277
>> You know, I'm not
sure of the answer.

898
00:48:00,310 --> 00:48:04,014

The Galilean Magnetometer
did some measurements

899
00:48:04,047 --> 00:48:06,650
as it went past
Io which did infer

900
00:48:06,683 --> 00:48:10,787
that there was, through
magnetic induction,

901
00:48:10,820 --> 00:48:13,824
that there was a
global magma ocean.

902
00:48:15,825 --> 00:48:18,295
I'm not sure about
the strength and size

903
00:48:18,328 --> 00:48:20,730
of Io's magnetic field.

904
00:48:20,763 --> 00:48:22,599
>> Thank you very much.

905
00:48:23,633 --> 00:48:24,868
>> Hi.

906
00:48:24,901 --> 00:48:27,037
My question is, do we
have an understanding

907
00:48:27,070 --> 00:48:31,007
of the mechanism from placement
of the magma at the surface?

908
00:48:31,040 --> 00:48:33,243
Is there some sort
of tectonism going on

909
00:48:33,276 --> 00:48:35,312
that is a mechanism for that?

910
00:48:35,345 --> 00:48:36,813
>> Right.

911
00:48:36,846 --> 00:48:38,381
We don't think there's any
sort of global tectonics

912
00:48:38,414 --> 00:48:41,151
the way we see global
tectonics on Earth.

913
00:48:41,184 --> 00:48:43,820
Instead, we have a
heat pipe mechanism

914
00:48:43,853 --> 00:48:48,124
where lava or magma works
its way up from the top

915
00:48:48,157 --> 00:48:50,994
of the lithosphere
to the surface.

916
00:48:53,329 --> 00:48:56,900
What helps it get there
seems to be a trend

917
00:48:58,601 --> 00:49:02,372
for large faults in the crust
providing planes of weakness

918
00:49:02,405 --> 00:49:05,742
and reducing stress,
horizontal stress,

919
00:49:07,143 --> 00:49:09,412

which provides pathways for
lava to get the surface.

920
00:49:09,445 --> 00:49:12,015
The problem with Io is it's
being resurfaced so fast

921
00:49:12,048 --> 00:49:14,384
that the crust is
getting compressed down.

922
00:49:14,417 --> 00:49:18,322
And so very large horizontal
stresses build up,

923
00:49:19,655 --> 00:49:21,257
and these stresses are relieved

924
00:49:21,290 --> 00:49:23,193
by large crustal blocks tilting

925
00:49:23,226 --> 00:49:26,096
and by faulting in other areas.

926
00:49:26,129 --> 00:49:28,298
And these seem to
provide pathways for lava

927
00:49:28,331 --> 00:49:29,933
to get to the surface.

928
00:49:29,966 --> 00:49:34,137
So the thick, the thick
crust seems to be fractured

929
00:49:37,874 --> 00:49:41,378
sufficiently to allow
the passage of lava,

930

00:49:42,812 --> 00:49:46,416
the passage of magma, to the
surface in many locations.

931
00:49:46,449 --> 00:49:49,919
But there are no plate tectonics
like what we see on earth.

932
00:49:49,952 --> 00:49:51,454
>> Audience Member: It's
fracturing, but there's no...

933
00:49:51,487 --> 00:49:53,590
>> It's fracturing, but
there's no subduction,

934
00:49:53,623 --> 00:49:55,992
and there's no sort of...

935
00:49:56,025 --> 00:49:59,429
There don't seem to be
any spreading centers.

936
00:49:59,462 --> 00:50:00,964
>> Okay, thank you.

937
00:50:02,398 --> 00:50:03,767
>> All right, you may not
be able to answer this,

938
00:50:03,800 --> 00:50:06,870
but I can't help but wondering
if the Europa Clipper

939
00:50:06,903 --> 00:50:08,905
might be carrying an
instrument that perhaps

940
00:50:08,938 --> 00:50:11,207
in an extended

mission could collect

941
00:50:11,240 --> 00:50:13,743
some of the data that
you're looking for from Io.

942
00:50:13,776 --> 00:50:14,978
>> Yep.

943
00:50:15,011 --> 00:50:16,212
We're still trying to
figure out what to look

944
00:50:16,245 --> 00:50:18,081
at on Europa with
the Europa Clipper,

945
00:50:18,114 --> 00:50:21,284
and Europa Clipper is not
going to make any close passes

946
00:50:21,317 --> 00:50:25,488
to Io because Io is deep in
Jupiter's radiation belt.

947
00:50:25,521 --> 00:50:29,693
So I think the best chance for
understanding Io's volcanism

948
00:50:30,960 --> 00:50:33,530
is with a dedicated Io mission.

949
00:50:37,300 --> 00:50:38,568
>> Two questions.

950
00:50:38,601 --> 00:50:41,471
The second one I guess
was already answered,

951

00:50:41,504 --> 00:50:42,806
that we're not going to...

952
00:50:42,839 --> 00:50:45,642
The Europa Clipper isn't
going to help here.

953
00:50:45,675 --> 00:50:49,512
So, if the energy
for all this activity

954
00:50:49,545 --> 00:50:51,915
is coming from the tidal forces

955
00:50:51,948 --> 00:50:54,351
between different satellites,

956
00:50:56,219 --> 00:51:00,156
is there enough energy
in that orbital motion

957
00:51:00,189 --> 00:51:05,195
to power the heat for the whole
lifetime of the solar system

958
00:51:05,228 --> 00:51:08,398
and for a billion
years in the future?

959
00:51:09,398 --> 00:51:11,168
>> It looks like Io...

960
00:51:13,002 --> 00:51:15,672
One of the theories about
Io and Europa and Ganymede

961
00:51:15,705 --> 00:51:19,876
is that they move in and
out of orbital resonance.

962
00:51:21,244 --> 00:51:25,148
So what we see is a
complicated byplay

963
00:51:25,181 --> 00:51:29,352
between orbital dynamics and
the interior structure of Io,

964
00:51:33,222 --> 00:51:34,991
Europa, and Ganymede.

965
00:51:36,058 --> 00:51:37,327
So it looks like, on a scale

966
00:51:37,360 --> 00:51:39,295
of maybe hundreds of
millions of years,

967
00:51:39,328 --> 00:51:40,964
Io and the other satellites

968
00:51:40,997 --> 00:51:43,600
may move in and out
of the resonance,

969
00:51:43,633 --> 00:51:46,469
which would actually
cut off volcanism on Io.

970
00:51:46,502 --> 00:51:49,973
So it might be that Io is
going through at the moment

971
00:51:50,006 --> 00:51:52,408
a very high level of
volcanic activity,

972
00:51:52,441 --> 00:51:55,445
'cause it's at a

peak in this scale.

973
00:51:56,379 --> 00:51:57,981
We don't really know,

974
00:51:58,014 --> 00:52:01,351
but that's important
because you get to the point

975
00:52:01,384 --> 00:52:05,622
where Io's interior is so
fluid that the tidal forces

976
00:52:07,723 --> 00:52:10,460
end up moving, just basically
moving the fluid around,

977
00:52:10,493 --> 00:52:13,796
and volcanism will
actually come to an end

978
00:52:13,829 --> 00:52:17,400
once it moves out
of the resonance.

979
00:52:17,433 --> 00:52:20,970
Once it's out of the
resonance and the tidal forces

980
00:52:21,003 --> 00:52:23,439
can get a grip on
a solid Io again,

981
00:52:23,472 --> 00:52:24,908
it will move back
into resonance,

982
00:52:24,941 --> 00:52:27,710
and the volcanism
will start again.

983
00:52:27,743 --> 00:52:29,212
And this might happen so quickly

984
00:52:29,245 --> 00:52:33,316
that we get total mixing or
total melting of the interior

985
00:52:36,319 --> 00:52:38,555
so that we go back to basalt,

986
00:52:38,588 --> 00:52:41,457
we go back to possibly
ultramafic material.

987
00:52:41,490 --> 00:52:45,562
It's a conveyor belt
of volcanic activity

988
00:52:45,595 --> 00:52:47,097
that moves so fast

989
00:52:48,564 --> 00:52:52,902
that we don't get
highly-evolved melts on Io.

990
00:52:52,935 --> 00:52:57,740
We don't get highly silicate,
highly silicon-content lavas

991
00:52:57,773 --> 00:52:58,942
like we see on earth.

992
00:52:58,975 --> 00:53:01,878
We don't get a
secondary crust forming

993
00:53:01,911 --> 00:53:03,580
or tertiary crust forming.

994
00:53:03,613 --> 00:53:07,784
So, it might be that Io is
heated back to an extent

995
00:53:11,487 --> 00:53:15,058
where it's a primitive
interior composition,

996
00:53:15,091 --> 00:53:16,659
which is why it's interesting,

997
00:53:16,692 --> 00:53:19,362
because that would
reflect the early earth.

998
00:53:19,395 --> 00:53:20,196
>> Very interesting.

999
00:53:20,229 --> 00:53:21,064
Thank you.

1000
00:53:23,299 --> 00:53:24,200
>> Great talk, Ashley.

1001
00:53:24,233 --> 00:53:26,202
I have a question and a comment.

1002
00:53:26,235 --> 00:53:27,770
The question is,

1003
00:53:27,803 --> 00:53:31,174
given all of the
modeling that you've done

1004
00:53:31,207 --> 00:53:34,477
and now it looks like we
also see cryovolcanism,

1005
00:53:34,510 --> 00:53:35,745
as you mentioned previously,

1006
00:53:35,778 --> 00:53:38,948
in places like Titan,
Enceladus, and Triton.

1007
00:53:38,981 --> 00:53:41,451
To what extent can
you apply the models

1008
00:53:41,484 --> 00:53:45,321
that you've developed for
sort of magma to cryomagmas,

1009
00:53:45,354 --> 00:53:47,991
and then the comment is
that today does happen

1010
00:53:48,024 --> 00:53:50,093
to be the 14th anniversary
of when Galileo

1011
00:53:50,126 --> 00:53:52,862
did its plunge into
Jupiter's atmosphere.

1012
00:53:52,895 --> 00:53:54,063
So it's quite
appropriate, I think,

1013
00:53:54,096 --> 00:53:55,465
that you gave this talk tonight.

1014
00:53:55,498 --> 00:53:56,600
>> Right, yes.

1015
00:53:58,901 --> 00:54:03,073
The physics of the eruption

and cooling and emplacement

1016
00:54:05,775 --> 00:54:09,679
of cryolavas, it's very
similar to the modeling

1017
00:54:11,714 --> 00:54:13,383
that I've been
doing, and basically

1018
00:54:13,416 --> 00:54:17,587
it's just the physical input
values that are changing.

1019
00:54:17,620 --> 00:54:21,791
So, yes, I've looked at the
emplacement of cryolavas

1020
00:54:23,159 --> 00:54:26,830
on Titan and some of the
effects on Enceladus as well.

1021
00:54:31,667 --> 00:54:34,304
Okay, we have some questions,

1022
00:54:34,337 --> 00:54:36,673
questions from the internet.

1023
00:54:37,573 --> 00:54:39,576
So, FindingFreedom asks,

1024
00:54:41,043 --> 00:54:43,513
"Could debris and particles
from Io's volcanic eruptions

1025
00:54:43,546 --> 00:54:46,716
"damage spacecraft orbiting
or flying by the moon?"

1026

00:54:46,749 --> 00:54:50,019
The answer is yes, they could.

1027
00:54:50,052 --> 00:54:52,555
Galileo itself had its orbits,

1028
00:54:54,824 --> 00:54:58,928
its orbital trajectory
changed to avoid a large plume

1029
00:55:00,129 --> 00:55:01,931
and ended up running
into another plume.

1030
00:55:01,964 --> 00:55:03,399
[audience laughs]

1031
00:55:03,432 --> 00:55:05,935
That's just the way it is.

1032
00:55:05,968 --> 00:55:09,772
But it is possible to
damage a spacecraft,

1033
00:55:09,805 --> 00:55:13,309
and that really depends on
what kind of plume is erupting,

1034
00:55:13,342 --> 00:55:14,777
how thick it is,

1035
00:55:14,810 --> 00:55:17,680
how much material has
been incorporated into it.

1036
00:55:17,713 --> 00:55:20,216
Your spacecraft is basically
flying through this

1037

00:55:20,249 --> 00:55:22,819
at about six or seven
kilometers a second,

1038
00:55:22,852 --> 00:55:26,022
so even small particles
can do damage.

1039
00:55:27,356 --> 00:55:30,326
Alex asks, "Do the
volcanoes act differently

1040
00:55:30,359 --> 00:55:34,630
"being directly exposed
to the vacuum of space?"

1041
00:55:34,663 --> 00:55:36,332
And that's a good question.

1042
00:55:36,365 --> 00:55:40,537
On earth, Old Faithful goes
up about 30 or 40 meters.

1043
00:55:44,407 --> 00:55:47,911
On Io, under the same
eruption conditions,

1044
00:55:49,445 --> 00:55:51,381
because you are
erupting into a vacuum

1045
00:55:51,414 --> 00:55:53,249
and because gravity is lower.

1046
00:55:53,282 --> 00:55:54,684
If it was just gravity lower,

1047
00:55:54,717 --> 00:55:58,254
the plume would be
six times higher,

1048
00:55:58,287 --> 00:56:00,189
but because you're
erupting into a vacuum,

1049
00:56:00,222 --> 00:56:01,591
you get much more expansion.

1050
00:56:01,624 --> 00:56:02,925
You get much more
bang for the buck.

1051
00:56:02,958 --> 00:56:05,762
Old Faithful would be
38 kilometers high.

1052
00:56:05,795 --> 00:56:09,332
So erupting into a
vacuum means that

1053
00:56:09,365 --> 00:56:12,835
if there's any gas
exsolving from the lava,

1054
00:56:12,868 --> 00:56:15,671
you tend to erupt
much higher velocities

1055
00:56:15,704 --> 00:56:18,908
than on Earth where things
are a little controlled

1056
00:56:18,941 --> 00:56:20,944
by atmospheric pressure.

1057
00:56:22,411 --> 00:56:24,781
And finally, Paige asks,

1058
00:56:24,814 --> 00:56:27,049

"Is there topographical
information

1059
00:56:27,082 --> 00:56:27,884
about Io's
lava lakes?

1060
00:56:27,917 --> 00:56:29,018
"I'd be curious to see

1061
00:56:29,051 --> 00:56:32,222
"the heights and
depths of Loki Patera."

1062
00:56:33,589 --> 00:56:36,392
We have a pretty sparse dataset
where there's high enough

1063
00:56:36,425 --> 00:56:39,595
resolution to make any
kinds of measurements

1064
00:56:39,628 --> 00:56:42,765
of lava flows and the lava lake.

1065
00:56:42,798 --> 00:56:45,234
The lava lake just seems
to be completely flat.

1066
00:56:45,267 --> 00:56:47,170
We see specular reflection
off the surface,

1067
00:56:47,203 --> 00:56:49,773
which kind of enhances the idea

1068
00:56:52,007 --> 00:56:54,343
that it is, in
fact, a lava lake.

1069
00:56:54,376 --> 00:56:57,547
There is only one measurement,
direct measurement,

1070
00:56:57,580 --> 00:56:59,849
of the thickness of
a lava flow on Io,

1071
00:56:59,882 --> 00:57:01,918
and that is about
10 meters thick

1072
00:57:01,951 --> 00:57:04,954
at a location called
Pillan Paterae

1073
00:57:06,589 --> 00:57:08,357
where there was a
big eruption in 1997,

1074
00:57:08,390 --> 00:57:10,226
which emplaced really
large lava flows,

1075
00:57:10,259 --> 00:57:11,994
which, in the space
of a few months,

1076
00:57:12,027 --> 00:57:15,364
covered 5600 square kilometers.

1077
00:57:15,397 --> 00:57:18,334
And these flows ended up
about 10 meters thick,

1078
00:57:18,367 --> 00:57:20,169
about 30 feet.

1079
00:57:20,202 --> 00:57:21,370

Okay, that's the last question.

1080
00:57:21,403 --> 00:57:24,140
Does anyone else
have any questions?

1081
00:57:27,510 --> 00:57:28,878
Well, thank you very
much for coming tonight.

1082
00:57:28,911 --> 00:57:29,912
[audience applauds]