FEELING HOT, HOT, HOT! MAGMA OCEAN EVOLUTION ON ROCKY (EXO)PLANETS

LAURA SCHAEFER

1
00:00:10,810 --> 00:00:07,080
[Music]

2
00:00:13,209 --> 00:00:10,820
thank you so obviously we don't have a

3
00:00:15,730 --> 00:00:13,219
photo of an actual magma ocean so I

4
00:00:18,700 --> 00:00:15,740
found this this really pretty picture of

5
00:00:20,820 --> 00:00:18,710
a lava like near in Congo I'm gonna have

6
00:00:24,070 --> 00:00:20,830
like a couple of different versions of

7
00:00:28,240 --> 00:00:24,080
photos of this lava lake but you can see

8
00:00:30,310 --> 00:00:28,250
this is looking at a pool of lava that

9
00:00:33,490 --> 00:00:30,320
is on the surface of a planet and it's

10
00:00:34,930 --> 00:00:33,500
got volatile is coming out of it so this

11
00:00:38,619 --> 00:00:34,940
is sort of the effect we're gonna talk

12
00:00:42,729 --> 00:00:38,629
about a lot is the interaction of lavas

13
00:00:45,250 --> 00:00:42,739

and volatile elements in the composition

14
00:00:47,829 --> 00:00:45,260
and the evolution of atmospheres on

15
00:00:50,439 --> 00:00:47,839
planets with magma oceans and I want to

16
00:00:53,290 --> 00:00:50,449
take a minute just to recognize my

17
00:00:56,289 --> 00:00:53,300
collaborators many of whom are here

18
00:00:59,169 --> 00:00:56,299
Kavi polygons are our chair Robyn

19
00:01:01,329 --> 00:00:59,179
Wordsworth Edwin kite secret Rondon and

20
00:01:03,279 --> 00:01:01,339
then of course my my former advisors

21
00:01:05,680 --> 00:01:03,289
Linda Elkins Hinton and Bruce Phegley

22
00:01:08,800 --> 00:01:05,690
and to the choice a celeb as well like

23
00:01:11,230 --> 00:01:08,810
to put on this way anyway so let's start

24
00:01:14,350 --> 00:01:11,240
with a little disco description of what

25
00:01:15,969 --> 00:01:14,360
exactly a magma ocean is and for the

26
00:01:19,240 --> 00:01:15,979
purposes of my track I'm just going to

27
00:01:22,630 --> 00:01:19,250
call it magma ocean anything that is a a

28
00:01:25,410 --> 00:01:22,640
very large body of silicate melts which

29
00:01:29,109 --> 00:01:25,420
may have some sort of crystals within it

30
00:01:32,889 --> 00:01:29,119
that is occupying a large portion of the

31
00:01:35,469 --> 00:01:32,899
surface of a terrestrial planet the

32
00:01:38,349 --> 00:01:35,479
figure on the Left sorry on the right

33
00:01:41,499 --> 00:01:38,359
here is showing how we usually think

34
00:01:43,179 --> 00:01:41,509
that magma oceans are evolving based on

35
00:01:48,370 --> 00:01:43,189
the temperature structure within the

36
00:01:50,380 --> 00:01:48,380
planet so this the red portions here are

37
00:01:51,999 --> 00:01:50,390
where we have silicate liquid blues

38
00:01:53,980 --> 00:01:52,009

portions are we have where we have

39
00:01:55,779 --> 00:01:53,990
solidified magma ocean and the screen

40
00:01:57,849 --> 00:01:55,789
down here at the bottom is assuming that

41
00:02:00,969 --> 00:01:57,859
we didn't fully melt our mantle so we

42
00:02:03,160 --> 00:02:00,979
have some unmelted residual down at the

43
00:02:05,440 --> 00:02:03,170
bottom of the planet I'm the black

44
00:02:07,929 --> 00:02:05,450
curves here are the melting temperatures

45
00:02:10,540 --> 00:02:07,939
of the silicate that's making up this

46
00:02:12,700 --> 00:02:10,550
planet for those of you who don't think

47
00:02:13,990 --> 00:02:12,710
about silicate melts um it's important

48
00:02:15,880 --> 00:02:14,000
to remember that they are multi

49
00:02:17,760 --> 00:02:15,890
component species and so they don't have

50
00:02:20,940 --> 00:02:17,770
a single melting point

51
00:02:23,760 --> 00:02:20,950
they have to the solidus is the point at

52
00:02:26,100 --> 00:02:23,770
which the first little bit of mount

53
00:02:27,990 --> 00:02:26,110
forms in the system and then we also

54
00:02:28,680 --> 00:02:28,000
have the liquidus which is this curve

55
00:02:37,290 --> 00:02:28,690
here

56
00:02:40,170 --> 00:02:37,300
of silicate is finally melting so in

57
00:02:44,430 --> 00:02:40,180
this region in between we have partial

58
00:02:46,560 --> 00:02:44,440
melt and so we have sort of this this

59
00:02:48,390 --> 00:02:46,570
dash line is sort of the dividing line

60
00:02:52,740 --> 00:02:48,400
between why we would think of this as

61
00:02:56,520 --> 00:02:52,750
more liquid present within a solid

62
00:02:58,320 --> 00:02:56,530
matrix of crystals versus a solid sort

63
00:03:01,590 --> 00:02:58,330

of floating around in what is dominantly

64
00:03:03,930 --> 00:03:01,600
a liquid in this upper region okay so

65
00:03:06,210 --> 00:03:03,940
the verdict more or less vertical lines

66
00:03:08,940 --> 00:03:06,220
here with the temperatures at the top

67
00:03:11,610 --> 00:03:08,950
are 80 of bats so we think was in the

68
00:03:14,010 --> 00:03:11,620
silicate mount portion within the melt

69
00:03:15,360 --> 00:03:14,020
the viscosity is pretty low and studies

70
00:03:17,700 --> 00:03:15,370
are convecting on pretty rapid

71
00:03:19,860 --> 00:03:17,710
timescales and so the temperature

72
00:03:22,590 --> 00:03:19,870
profile of the magma ocean is following

73
00:03:24,510 --> 00:03:22,600
an 80 of that and for the purposes of

74
00:03:26,640 --> 00:03:24,520
the the model is then we are going to

75
00:03:28,770 --> 00:03:26,650
talk about here what we typically assume

76
00:03:30,990 --> 00:03:28,780
is that the 80 of that first intersects

77
00:03:33,900 --> 00:03:31,000
these melting points at the bottom of

78
00:03:35,480 --> 00:03:33,910
the mantle and so what's happening is we

79
00:03:38,010 --> 00:03:35,490
get the first a little bit of

80
00:03:40,830 --> 00:03:38,020
solidification is happening down at the

81
00:03:44,040 --> 00:03:40,840
bottom of your mantle and the remainder

82
00:03:45,690 --> 00:03:44,050
the top remains liquid and so if you

83
00:03:50,250 --> 00:03:45,700
have an atmosphere you'll be interacting

84
00:03:52,890 --> 00:03:50,260
with the liquid for the duration of the

85
00:03:54,900 --> 00:03:52,900
mag motion time period there is a little

86
00:03:57,420 --> 00:03:54,910
bit of a complication here and that we

87
00:03:58,230 --> 00:03:57,430
don't really know the melting profile of

88
00:03:59,640 --> 00:03:58,240

supers

89
00:04:02,699 --> 00:03:59,650
we don't really know melting profiles

90
00:04:05,699 --> 00:04:02,709
much beyond the pressure regime of the

91
00:04:09,300 --> 00:04:05,709
Earth's mantle and even that is somewhat

92
00:04:12,000 --> 00:04:09,310
disputed some experiments suggest that

93
00:04:13,560 --> 00:04:12,010
there is a bit of a curvature to the

94
00:04:15,060 --> 00:04:13,570
solidus and the liquidus that would

95
00:04:18,330 --> 00:04:15,070
indicate that you should start getting

96
00:04:22,290 --> 00:04:18,340
your first sort of crystals forming sort

97
00:04:25,640 --> 00:04:22,300
of in mid mantle regions where you might

98
00:04:28,110 --> 00:04:25,650
end up with a basal Mazal magma ocean

99
00:04:30,800 --> 00:04:28,120
with the planet sort of solidifying from

100
00:04:33,140 --> 00:04:30,810
both in both directions at the same time

101
00:04:34,490 --> 00:04:33,150
but for the models I'm mostly gonna be

102
00:04:37,990 --> 00:04:34,500
talking about today we're gonna assume

103
00:04:41,450 --> 00:04:38,000
that the solidus is nice and decreasing

104
00:04:42,950 --> 00:04:41,460
means so that we're only going to start

105
00:04:46,670 --> 00:04:42,960
solidifying at the bottom of the mantle

106
00:04:49,220 --> 00:04:46,680
um so I'm gonna talk to split this talk

107
00:04:51,890 --> 00:04:49,230
up a little bit into first where do we

108
00:04:55,220 --> 00:04:51,900
find magma oceans and then talk a little

109
00:04:58,010 --> 00:04:55,230
bit more after that about the the

110
00:05:00,620 --> 00:04:58,020
dominant processes that different kinds

111
00:05:02,780 --> 00:05:00,630
of magma oceans would experience so

112
00:05:05,450 --> 00:05:02,790
let's start first with where do we find

113
00:05:07,790 --> 00:05:05,460

magma oceans this is just another

114
00:05:10,280 --> 00:05:07,800
schematic of a magma ocean here where we

115
00:05:12,260 --> 00:05:10,290
have the convecting liquid and crystals

116
00:05:15,580 --> 00:05:12,270
falling out towards the bottom of mantle

117
00:05:19,370 --> 00:05:15,590
and we have an atmosphere on top so

118
00:05:21,740 --> 00:05:19,380
there's sort of three major places where

119
00:05:24,460 --> 00:05:21,750
where I think we're finding magma oceans

120
00:05:28,010 --> 00:05:24,470
and these are sort of separated by the

121
00:05:30,050 --> 00:05:28,020
dominant heat source that's producing

122
00:05:32,180 --> 00:05:30,060
these magma oceans and I left one off

123
00:05:33,469 --> 00:05:32,190
here which is tidal heating I'm not

124
00:05:33,950 --> 00:05:33,479
going to talk about tidal heating here

125
00:05:36,170 --> 00:05:33,960
at all

126
00:05:37,700 --> 00:05:36,180
um so the first I'm going to talk about

127
00:05:39,820 --> 00:05:37,710
is young cleanness and this is what we

128
00:05:43,490 --> 00:05:39,830
usually think of for the solar system

129
00:05:46,880 --> 00:05:43,500
and a lot of the magma ocean models are

130
00:05:49,070 --> 00:05:46,890
really based on on models developed in

131
00:05:51,409 --> 00:05:49,080
the solar system especially those models

132
00:05:52,219 --> 00:05:51,419
developed by Matsui and obby in the

133
00:05:56,750 --> 00:05:52,229
mid-80s

134
00:05:59,719 --> 00:05:56,760
and for the formation of Earth and Venus

135
00:06:03,469 --> 00:05:59,729
and Mars so the figure on the left is

136
00:06:04,550 --> 00:06:03,479
showing the evolution of the mass and

137
00:06:07,159 --> 00:06:04,560
radius of the planet

138
00:06:09,710 --> 00:06:07,169

as it is growing from an accretion ulm

139
00:06:13,190 --> 00:06:09,720
aatul so the radius of the planet is

140
00:06:16,310 --> 00:06:13,200
increasing to the right on this x-axis

141
00:06:18,320 --> 00:06:16,320
here and the y-axis is showing the mass

142
00:06:21,310 --> 00:06:18,330
of the atmosphere and so what's

143
00:06:24,620 --> 00:06:21,320
happening thing is as volatile material

144
00:06:26,870 --> 00:06:24,630
material is coming in with the solid

145
00:06:28,730 --> 00:06:26,880
material and it's being delivered into

146
00:06:31,610 --> 00:06:28,740
the atmosphere so you have pretty rapid

147
00:06:34,610 --> 00:06:31,620
atmospheric growth um this figure on the

148
00:06:37,340 --> 00:06:34,620
right is from a related model from a Bay

149
00:06:39,320 --> 00:06:37,350
and is showing the evolution of the

150
00:06:41,690 --> 00:06:39,330
pressure and temperature at the surface

151
00:06:44,760 --> 00:06:41,700
of the planet as a result of many of

152
00:06:47,249 --> 00:06:44,770
these rapid impact

153
00:06:49,230 --> 00:06:47,259
so we have a rapid increase in the

154
00:06:51,689 --> 00:06:49,240
pressure as the mass of the atmosphere

155
00:06:53,550 --> 00:06:51,699
is growing and because these collisions

156
00:06:56,070 --> 00:06:53,560
are occurring quickly and the heat is

157
00:06:58,290 --> 00:06:56,080
not being dissipated the surface

158
00:06:59,850 --> 00:06:58,300
temperature of the planet is growing and

159
00:07:01,620 --> 00:06:59,860
it's growing here in a stochastic way

160
00:07:04,460 --> 00:07:01,630
because these are impacts of variable

161
00:07:08,270 --> 00:07:04,470
size and variable duration and so forth

162
00:07:11,249 --> 00:07:08,280
so this is sort of the standard picture

163
00:07:14,100 --> 00:07:11,259

that came out in the 80s and early 90s

164
00:07:17,159 --> 00:07:14,110
for how planets grew in the solar system

165
00:07:20,219 --> 00:07:17,169
and how the early atmosphere grew and

166
00:07:22,110 --> 00:07:20,229
this implies that you have these you

167
00:07:24,810 --> 00:07:22,120
know you have these massive surface

168
00:07:26,700 --> 00:07:24,820
temperatures that would require the the

169
00:07:29,879 --> 00:07:26,710
planets to become fully molten all the

170
00:07:32,210 --> 00:07:29,889
way through the other method in in

171
00:07:34,740 --> 00:07:32,220
addition to just this sort of singular

172
00:07:37,920 --> 00:07:34,750
and many small impacts could produce

173
00:07:39,719 --> 00:07:37,930
this this magma ocean now the more

174
00:07:43,080 --> 00:07:39,729
favourable method for doing this is a

175
00:07:47,400 --> 00:07:43,090
singular giant impact such as the one

176
00:07:49,890 --> 00:07:47,410
that we think created the first moon in

177
00:07:51,510 --> 00:07:49,900
fact the moon is actually the only

178
00:07:54,570 --> 00:07:51,520
object in the solar system for which we

179
00:07:57,330 --> 00:07:54,580
have solid evidence that there in fact

180
00:08:00,060 --> 00:07:57,340
was a magma ocean every other planet

181
00:08:01,710 --> 00:08:00,070
including the earth and Venus and in

182
00:08:03,060 --> 00:08:01,720
many of the small planetesimals that

183
00:08:07,260 --> 00:08:03,070
people think had many motions

184
00:08:10,430 --> 00:08:07,270
it's all very circumstantial but for the

185
00:08:13,610 --> 00:08:10,440
moon people had originally thought that

186
00:08:18,210 --> 00:08:13,620
when the first apollo samples came back

187
00:08:20,550 --> 00:08:18,220
the composition of the crust of the moon

188
00:08:23,249 --> 00:08:20,560

is shown in this this sort of diagram

189
00:08:25,640 --> 00:08:23,259
over here this is sort of a less

190
00:08:29,640 --> 00:08:25,650
colorful version of that diagram from

191
00:08:32,790 --> 00:08:29,650
1970 the crust of the moon is made of

192
00:08:34,680 --> 00:08:32,800
this component called anorthosite it's a

193
00:08:38,420 --> 00:08:34,690
it's Donnelly made out of the mineral

194
00:08:42,810 --> 00:08:38,430
inner site which is a very light

195
00:08:45,990 --> 00:08:42,820
low-density mineral and the way people

196
00:08:48,540 --> 00:08:46,000
thought that this was created this crust

197
00:08:52,019 --> 00:08:48,550
of in our society is that you have a

198
00:08:54,630 --> 00:08:52,029
magma ocean created as the Moon is

199
00:08:56,180 --> 00:08:54,640
forming by this giant impact you melt

200
00:08:58,130 --> 00:08:56,190
most of the planet and the

201
00:09:00,890 --> 00:08:58,140
begin fractionally crystallizing it and

202
00:09:03,230 --> 00:09:00,900
so what that means is that um your

203
00:09:05,390 --> 00:09:03,240
crystallizing different minerals out of

204
00:09:08,000 --> 00:09:05,400
the silicate melt within the magma ocean

205
00:09:10,490 --> 00:09:08,010
and it's separating out so those

206
00:09:12,320 --> 00:09:10,500
minerals are falling down to the bottom

207
00:09:14,990 --> 00:09:12,330
of the magma ocean and separating from

208
00:09:17,240 --> 00:09:15,000
the melt and so the milk composition is

209
00:09:19,550 --> 00:09:17,250
evolving and so then the minerals that

210
00:09:21,980 --> 00:09:19,560
are coming out next have a slightly

211
00:09:24,590 --> 00:09:21,990
different composition once you get to a

212
00:09:26,720 --> 00:09:24,600
certain fraction of Mount crystallized

213
00:09:29,600 --> 00:09:26,730

you can begin to crystallize this

214
00:09:32,330 --> 00:09:29,610
mineral and our site which turns out to

215
00:09:34,910 --> 00:09:32,340
be lower density than the silicate

216
00:09:37,880 --> 00:09:34,920
liquid it's crystallizing out of and so

217
00:09:41,660 --> 00:09:37,890
what happens is it floats it floats to

218
00:09:45,410 --> 00:09:41,670
the top and it makes this rich crust of

219
00:09:47,720 --> 00:09:45,420
the early moon and this process had been

220
00:09:49,910 --> 00:09:47,730
seen before on the earth in magma

221
00:09:53,180 --> 00:09:49,920
chambers we had seen an earth ID

222
00:09:55,550 --> 00:09:53,190
floatation crust with within magma

223
00:09:57,470 --> 00:09:55,560
chambers and there there are other

224
00:09:59,900 --> 00:09:57,480
pieces of evidence for the lunar magma

225
00:10:05,000 --> 00:09:59,910
ocean including there's a component

226
00:10:06,890 --> 00:10:05,010
called creep kr EEP for potassium rare

227
00:10:08,750 --> 00:10:06,900
earth elements and phosphorus

228
00:10:11,270 --> 00:10:08,760
this is appears to be that's sort of the

229
00:10:14,030 --> 00:10:11,280
residual of the magma ocean it's the

230
00:10:16,160 --> 00:10:14,040
last little bit that crystallized and it

231
00:10:18,290 --> 00:10:16,170
has all the incompatible elements that

232
00:10:21,200 --> 00:10:18,300
didn't want to freeze out in the earlier

233
00:10:23,810 --> 00:10:21,210
stages of crystallization and then the

234
00:10:26,210 --> 00:10:23,820
other sort of evidence for lunar magma

235
00:10:28,670 --> 00:10:26,220
ocean comes from the ages of these

236
00:10:31,310 --> 00:10:28,680
crustal materials that were brought back

237
00:10:33,890 --> 00:10:31,320
by Apollo and from lunar meteorites this

238
00:10:35,960 --> 00:10:33,900

is a timeline of lunar formation and

239
00:10:39,020 --> 00:10:35,970
differentiation from lineal Constanta

240
00:10:41,240 --> 00:10:39,030
and work on the lunar magma ocean where

241
00:10:44,000 --> 00:10:41,250
you can see lunar formation from giant

242
00:10:46,579 --> 00:10:44,010
impact is out here about 4.5 four

243
00:10:49,640 --> 00:10:46,589
billion years and you have the magma

244
00:10:52,610 --> 00:10:49,650
ocean sorry the formation of the moon

245
00:10:56,720 --> 00:10:52,620
from the disk of material that's ejected

246
00:10:59,720 --> 00:10:56,730
from the earth these bars over here are

247
00:11:01,790 --> 00:10:59,730
ages for lunar crustal materials and

248
00:11:03,500 --> 00:11:01,800
these are quite a bit older than most of

249
00:11:07,070 --> 00:11:03,510
the other materials that we have access

250
00:11:09,320 --> 00:11:07,080
to from planetary sized bodies and much

251
00:11:12,860 --> 00:11:09,330
older in fact than anything that we have

252
00:11:14,900 --> 00:11:12,870
me from the earth and then these blue

253
00:11:18,880 --> 00:11:14,910
bars are highlighting the predicted

254
00:11:22,370 --> 00:11:18,890
magma ocean lifetimes from models

255
00:11:23,810 --> 00:11:22,380
initial models put the lifetime at only

256
00:11:26,090 --> 00:11:23,820
ten million years which wasn't really

257
00:11:29,030 --> 00:11:26,100
enough to account for the ages of these

258
00:11:31,310 --> 00:11:29,040
many different minerals from the from

259
00:11:34,220 --> 00:11:31,320
the lunar surface but the addition of

260
00:11:39,170 --> 00:11:34,230
tidal heating allowed the extension of

261
00:11:42,230 --> 00:11:39,180
this crystallization timescale so this

262
00:11:44,420 --> 00:11:42,240
is again and this is amongst the best

263
00:11:46,880 --> 00:11:44,430

evidence that we have that magma oceans

264
00:11:49,910 --> 00:11:46,890
are a real phenomenon within the solar

265
00:11:52,579 --> 00:11:49,920
system now the giant impact would have

266
00:11:54,560 --> 00:11:52,589
almost inevitably also melted the earth

267
00:11:56,360 --> 00:11:54,570
but again we don't have much in the way

268
00:11:57,800 --> 00:11:56,370
of geologic evidence from this time

269
00:12:02,240 --> 00:11:57,810
period on the earth because the earth is

270
00:12:03,980 --> 00:12:02,250
a very geologically active body but we

271
00:12:08,000 --> 00:12:03,990
think it ended up with a massive

272
00:12:10,100 --> 00:12:08,010
atmosphere and it cooled well relatively

273
00:12:13,639 --> 00:12:10,110
quickly compared to many other planets

274
00:12:15,860 --> 00:12:13,649
um and we think that these giant impacts

275
00:12:18,860 --> 00:12:15,870
are pretty common and in planet

276
00:12:21,440 --> 00:12:18,870
formation this is from the work of Eliza

277
00:12:23,780 --> 00:12:21,450
Quintana looking at giant impact

278
00:12:25,880 --> 00:12:23,790
frequency in n-body simulations of

279
00:12:28,010 --> 00:12:25,890
planet formation and what she found was

280
00:12:31,069 --> 00:12:28,020
that for any given object if you track

281
00:12:33,699 --> 00:12:31,079
its impact history many of them

282
00:12:37,720 --> 00:12:33,709
experienced on the order of two to three

283
00:12:41,150 --> 00:12:37,730
giant impacts before they before the

284
00:12:43,760 --> 00:12:41,160
accretionary period is over so the earth

285
00:12:47,120 --> 00:12:43,770
likely the giant impact that formed the

286
00:12:49,550 --> 00:12:47,130
moon wasn't necessarily the first my

287
00:12:55,430 --> 00:12:49,560
giant impact generated mag motion that

288
00:12:57,920 --> 00:12:55,440

the earth experienced okay so moving on

289
00:13:00,530 --> 00:12:57,930
from a young planet so that's how you

290
00:13:03,250 --> 00:13:00,540
would potentially generate magnet oceans

291
00:13:05,990 --> 00:13:03,260
on large planets as they are forming

292
00:13:08,300 --> 00:13:06,000
amongst the exoplanet population we now

293
00:13:11,180 --> 00:13:08,310
have evidence for four planets that are

294
00:13:13,850 --> 00:13:11,190
extremely hot and they are likely bare

295
00:13:16,370 --> 00:13:13,860
rocky planets but nonetheless may have a

296
00:13:19,730 --> 00:13:16,380
magma ocean on their day side at least

297
00:13:22,519 --> 00:13:19,740
this is just a mass radius diagram where

298
00:13:24,980 --> 00:13:22,529
the planets are color-coded by the flux

299
00:13:27,439 --> 00:13:24,990
that they receive and converted here

300
00:13:29,360 --> 00:13:27,449
into an equilibrium temperature so I

301
00:13:31,759 --> 00:13:29,370
don't need and this is a sort of an

302
00:13:33,710 --> 00:13:31,769
artist's impression of Cobra 7b which

303
00:13:36,590 --> 00:13:33,720
was one of the first super Earths

304
00:13:39,170 --> 00:13:36,600
discovered by the co-wrote mission was

305
00:13:42,970 --> 00:13:39,180
shortly followed by Kepler 10b which has

306
00:13:45,769 --> 00:13:42,980
a very similar orbital period and

307
00:13:47,749 --> 00:13:45,779
equilibrium temperature so these first

308
00:13:49,790 --> 00:13:47,759
planets that we discovered in the super

309
00:13:52,400 --> 00:13:49,800
earth regime you know they have super

310
00:13:53,960 --> 00:13:52,410
Earths earth-like densities but they

311
00:13:56,799 --> 00:13:53,970
have temperatures equilibrium

312
00:14:01,519 --> 00:13:56,809
temperatures of around 2000 Kelvin and

313
00:14:05,210 --> 00:14:01,529

most basaltic melts form at temperatures

314
00:14:08,239 --> 00:14:05,220
of a thousand to 1200 Kelvin some up to

315
00:14:10,519 --> 00:14:08,249
1500 Kelvin so this is more than hot

316
00:14:13,939 --> 00:14:10,529
enough just from the stellar insulation

317
00:14:17,840 --> 00:14:13,949
to melt the surface the de sides of

318
00:14:20,179 --> 00:14:17,850
these planets um and then this the last

319
00:14:21,559 --> 00:14:20,189
kind of magma ocean planet that I want

320
00:14:23,780 --> 00:14:21,569
to talk about is these sort of hot

321
00:14:26,600 --> 00:14:23,790
runaway greenhouse when it set they

322
00:14:29,179 --> 00:14:26,610
again the the heat source here is still

323
00:14:30,949 --> 00:14:29,189
stellar insulation but the stellar

324
00:14:33,559 --> 00:14:30,959
insulation isn't sufficient without an

325
00:14:35,749 --> 00:14:33,569
atmosphere to melt the surface and in

326
00:14:37,910 --> 00:14:35,759
some cases some ways these are also

327
00:14:39,559 --> 00:14:37,920
related to the young planets because we

328
00:14:42,759 --> 00:14:39,569
think mag motions on the young planets

329
00:14:46,850 --> 00:14:42,769
are related to this greenhouse effect

330
00:14:49,309 --> 00:14:46,860
but the the main component of

331
00:14:52,610 --> 00:14:49,319
atmospheres that that people with solar

332
00:14:55,579 --> 00:14:52,620
system and modelling history like to use

333
00:14:57,860 --> 00:14:55,589
is water because water is one of the

334
00:14:59,720 --> 00:14:57,870
most abundant volatiles we don't see

335
00:15:02,299 --> 00:14:59,730
hydrogen helium atmospheres on rocky

336
00:15:05,540 --> 00:15:02,309
planets in the solar system and so this

337
00:15:08,059 --> 00:15:05,550
is the dominant volatile component and

338
00:15:09,799 --> 00:15:08,069

it's a very good greenhouse gas and so

339
00:15:11,269 --> 00:15:09,809
this is just a simple calculation that I

340
00:15:13,759 --> 00:15:11,279
did with sort of a great atmosphere

341
00:15:16,819 --> 00:15:13,769
model to see how much water you would

342
00:15:19,129 --> 00:15:16,829
need in the atmosphere of some of the

343
00:15:20,840 --> 00:15:19,139
known super-earth planets in order to

344
00:15:24,559 --> 00:15:20,850
bring the surface temperature up to two

345
00:15:26,480 --> 00:15:24,569
thousand Kelvin so the these the x-axis

346
00:15:28,970 --> 00:15:26,490
here is stellar insulation relative to

347
00:15:31,449 --> 00:15:28,980
the earth with the earth on the far left

348
00:15:34,699 --> 00:15:31,459
hand side and this y-axis is the

349
00:15:35,990 --> 00:15:34,709
pressure of water vapour in the

350
00:15:38,869 --> 00:15:36,000
atmosphere needed to

351
00:15:41,329 --> 00:15:38,879
melt the surface and for reference this

352
00:15:43,129 --> 00:15:41,339
dash line here is the amount of water on

353
00:15:46,160 --> 00:15:43,139
the surface of the earth today that's

354
00:15:49,910 --> 00:15:46,170
about 300 bars and so most of these need

355
00:15:53,059 --> 00:15:49,920
around one bar ten bars now whether

356
00:15:54,530 --> 00:15:53,069
that's a stable atmosphere or not it's a

357
00:15:56,689 --> 00:15:54,540
different matter but they don't need

358
00:16:00,619 --> 00:15:56,699
very much atmosphere at all to cause

359
00:16:04,340 --> 00:16:00,629
their surfaces to melt this is a very

360
00:16:05,540 --> 00:16:04,350
well-known subject that people have

361
00:16:09,290 --> 00:16:05,550
studied a lot this runaway greenhouse

362
00:16:11,150 --> 00:16:09,300
phenomenon for water-rich Worlds this is

363
00:16:14,480 --> 00:16:11,160

a calculation of the runaway greenhouse

364
00:16:17,139 --> 00:16:14,490
limit for a steam atmosphere from Cape

365
00:16:20,780 --> 00:16:17,149
Romano in this review paper by a coma

366
00:16:24,350 --> 00:16:20,790
this is the outgoing long-wave radiation

367
00:16:26,269 --> 00:16:24,360
from the planet as a function of the

368
00:16:28,460 --> 00:16:26,279
water vapor pressure in the atmosphere

369
00:16:30,980 --> 00:16:28,470
so you can see that as soon as you get

370
00:16:33,650 --> 00:16:30,990
above this runaway greenhouse threshold

371
00:16:36,710 --> 00:16:33,660
as you add water to your atmosphere you

372
00:16:39,559 --> 00:16:36,720
have to get out to really really hot

373
00:16:42,110 --> 00:16:39,569
temperatures in order to hit radio of

374
00:16:44,360 --> 00:16:42,120
equilibrium so if you say have a hundred

375
00:16:48,490 --> 00:16:44,370
bars of water vapor in your atmosphere

376
00:16:51,199 --> 00:16:48,500
and you're receiving a thousand watts of

377
00:16:52,699 --> 00:16:51,209
stellar radiation then your surface

378
00:16:56,509 --> 00:16:52,709
temperature is around two thousand

379
00:17:00,619 --> 00:16:56,519
Kelvin okay so I wanted to highlight

380
00:17:03,799 --> 00:17:00,629
here a poster by Denisha cut job on this

381
00:17:06,380 --> 00:17:03,809
kind of steam and co2 mixed atmosphere

382
00:17:09,140 --> 00:17:06,390
so you should go check out her poster

383
00:17:12,289 --> 00:17:09,150
i'm keiko maja mono has looked at at

384
00:17:14,929 --> 00:17:12,299
sort of the magma ocean occurrence as a

385
00:17:17,990 --> 00:17:14,939
function of cellar age and orbital

386
00:17:20,210 --> 00:17:18,000
distance for G dwarf stars the color

387
00:17:23,059 --> 00:17:20,220
coding here is the amount of water a

388
00:17:27,169 --> 00:17:23,069

planet needs to have to maintain a magma

389
00:17:30,020 --> 00:17:27,179
ocean for this stellar age these are

390
00:17:32,060 --> 00:17:30,030
planets orbiting G dwarfs she's

391
00:17:34,669 --> 00:17:32,070
highlighting here the giant impact stage

392
00:17:36,770 --> 00:17:34,679
so planets out here at Earth orbit

393
00:17:40,010 --> 00:17:36,780
cannot really maintain a magma ocean

394
00:17:42,710 --> 00:17:40,020
beyond the giant impact stage the magma

395
00:17:44,779 --> 00:17:42,720
oceans cool off much too quickly there's

396
00:17:47,360 --> 00:17:44,789
this sort of critical orbital distance

397
00:17:48,430 --> 00:17:47,370
at which point at some point the planet

398
00:17:50,320 --> 00:17:48,440
cools off to

399
00:17:52,779 --> 00:17:50,330
a point where you can get liquid water

400
00:17:56,980 --> 00:17:52,789
to form and once that does the runaway

401
00:18:00,279 --> 00:17:56,990
greenhouse atmosphere collapses and you

402
00:18:03,879 --> 00:18:00,289
get a significant drop in your surface

403
00:18:05,799 --> 00:18:03,889
temperature so for this sort of Venus

404
00:18:08,799 --> 00:18:05,809
like orbital period you get this sort of

405
00:18:12,249 --> 00:18:08,809
peak if you have like one earth ocean of

406
00:18:14,409 --> 00:18:12,259
water in the length of time that you can

407
00:18:16,330 --> 00:18:14,419
have your magma ocean surviving and of

408
00:18:21,180 --> 00:18:16,340
course the more water you have the

409
00:18:24,610 --> 00:18:21,190
longer your mag motion can survive um

410
00:18:27,850 --> 00:18:24,620
okay so I'm gonna jump now to talking

411
00:18:29,830 --> 00:18:27,860
about some of more of the dynamics and

412
00:18:31,990 --> 00:18:29,840
the chemistry of the processes going on

413
00:18:33,759 --> 00:18:32,000

on these different kinds of planets I'm

414
00:18:35,710 --> 00:18:33,769
gonna come back to those planets that

415
00:18:38,740 --> 00:18:35,720
are very volatile rich and I'm gonna

416
00:18:42,639 --> 00:18:38,750
start first of all with the lava worlds

417
00:18:46,810 --> 00:18:42,649
discovered in the exoplanet sample I

418
00:18:48,970 --> 00:18:46,820
mean I'm gonna start with my with some

419
00:18:51,430 --> 00:18:48,980
of the initial models for that were

420
00:18:54,159 --> 00:18:51,440
based on Co row 7 being Kepler 10b this

421
00:18:56,440 --> 00:18:54,169
is sort of an artist's impression from

422
00:19:00,039 --> 00:18:56,450
this big paper by Elaine Legare and and

423
00:19:02,710 --> 00:19:00,049
many many co-authors so this is an

424
00:19:04,210 --> 00:19:02,720
artist rendition of what this planet

425
00:19:06,730 --> 00:19:04,220
would look like the assumption being

426
00:19:09,129 --> 00:19:06,740
that this planet is tidally locked and

427
00:19:11,110 --> 00:19:09,139
synchronously rotating and so it has a

428
00:19:13,389 --> 00:19:11,120
permanent dayside in a permanent night

429
00:19:18,340 --> 00:19:13,399
side and that permanent day side is

430
00:19:20,680 --> 00:19:18,350
covered with a lava pool with of course

431
00:19:22,210 --> 00:19:20,690
the peak temperature occurring at the

432
00:19:25,810 --> 00:19:22,220
sub stellar point and dropping off

433
00:19:28,600 --> 00:19:25,820
rapidly towards the Terminator and so

434
00:19:30,820 --> 00:19:28,610
the the edges of this magma ocean pool

435
00:19:32,350 --> 00:19:30,830
are going to occur before you hit the

436
00:19:35,830 --> 00:19:32,360
Terminator because the Terminator is

437
00:19:38,769 --> 00:19:35,840
quite cold and the atmospheric pressure

438
00:19:41,799 --> 00:19:38,779

is determined here under the assumption

439
00:19:46,269 --> 00:19:41,809
that these planets are volatile free by

440
00:19:49,240 --> 00:19:46,279
a silicate vaporization model so this

441
00:19:51,749 --> 00:19:49,250
was based on some of our previous models

442
00:19:54,820 --> 00:19:51,759
that we had actually developed for

443
00:19:58,269 --> 00:19:54,830
modeling the composition of volcanic

444
00:20:00,910 --> 00:19:58,279
gasses on Jupiter's moon Io this is the

445
00:20:05,110 --> 00:20:00,920
the predicted gas composition as a

446
00:20:05,740 --> 00:20:05,120
action of temperature for for a silicate

447
00:20:09,040 --> 00:20:05,750
melts

448
00:20:11,530 --> 00:20:09,050
where the dominant gas here is sodium

449
00:20:13,270 --> 00:20:11,540
because sodium is a very volatile

450
00:20:16,690 --> 00:20:13,280
relatively volatile element in a

451
00:20:21,240 --> 00:20:16,700
silicate system and the the next most

452
00:20:24,520 --> 00:20:21,250
abundant gases are oxygen and co2

453
00:20:26,170 --> 00:20:24,530
because oxygen is in fact the most

454
00:20:27,580 --> 00:20:26,180
abundant element in silicate melt

455
00:20:30,300 --> 00:20:27,590
systems and then you have things like

456
00:20:34,540 --> 00:20:30,310
silicon monoxide and magnesium and iron

457
00:20:38,080 --> 00:20:34,550
atomic species I mean this model also

458
00:20:42,820 --> 00:20:38,090
looked at fractional evaporation of this

459
00:20:45,490 --> 00:20:42,830
system so if you have a massive pressure

460
00:20:47,920 --> 00:20:45,500
gradient you should expect to get winds

461
00:20:49,690 --> 00:20:47,930
driving away from this sub stellar point

462
00:20:52,390 --> 00:20:49,700
where most of your material is

463
00:20:55,240 --> 00:20:52,400

evaporating and might cause some

464
00:20:57,970 --> 00:20:55,250
compositional evolution of this pool and

465
00:21:00,280 --> 00:20:57,980
this model handles the fractional

466
00:21:02,200 --> 00:21:00,290
vaporization the x-axis here is the

467
00:21:05,500 --> 00:21:02,210
fraction of the silicate that has

468
00:21:08,680 --> 00:21:05,510
evaporated and this is showing the

469
00:21:12,060 --> 00:21:08,690
composition of the gas phase so what you

470
00:21:14,950 --> 00:21:12,070
see is that the sodium and potassium are

471
00:21:16,390 --> 00:21:14,960
depleted the first from this melt pool

472
00:21:19,210 --> 00:21:16,400
because they're the most volatile

473
00:21:22,800 --> 00:21:19,220
elements present followed by iron iron

474
00:21:25,500 --> 00:21:22,810
is in fact very volatile and followed

475
00:21:27,940 --> 00:21:25,510
and after the words you have a

476
00:21:29,920 --> 00:21:27,950
composition mostly dominated by silicon

477
00:21:31,870 --> 00:21:29,930
magnesium and if you keep going far

478
00:21:37,770 --> 00:21:31,880
enough you'll get out to a composition

479
00:21:44,950 --> 00:21:43,240
Ito at all in 2015 did another round of

480
00:21:47,140 --> 00:21:44,960
calculations of this kind of silicate

481
00:21:49,360 --> 00:21:47,150
vapor atmosphere and they calculated

482
00:21:52,720 --> 00:21:49,370
temperature and pressure profiles for

483
00:21:54,850 --> 00:21:52,730
different sort of substellar equilibrium

484
00:21:56,680 --> 00:21:54,860
temperatures and what they found was

485
00:21:59,860 --> 00:21:56,690
that once you get above the knee Coulomb

486
00:22:02,530 --> 00:21:59,870
temperature of about 2000 Kelvin you end

487
00:22:06,270 --> 00:22:02,540
up getting a temperature inversion in

488
00:22:10,060 --> 00:22:06,280

the atmosphere and then I calculated the

489
00:22:12,659 --> 00:22:10,070
secondary Eclipse steps for a variety of

490
00:22:16,830 --> 00:22:12,669
these lava world planet

491
00:22:18,600 --> 00:22:16,840
um from the infrared out to the the Fox

492
00:22:20,970 --> 00:22:18,610
and sorry the the optical out to the

493
00:22:22,529 --> 00:22:20,980
far-infrared and you get some features

494
00:22:24,480 --> 00:22:22,539
coming from the atmosphere you have

495
00:22:26,820 --> 00:22:24,490
sodium and potassium lines and the

496
00:22:28,320 --> 00:22:26,830
optical and these features here I

497
00:22:32,240 --> 00:22:28,330
believe are due to the silicon monoxide

498
00:22:35,659 --> 00:22:32,250
gas so those are potentially observable

499
00:22:39,149 --> 00:22:35,669
with James Webb and the other

500
00:22:42,690 --> 00:22:39,159
observational tests you can make for

501
00:22:45,629 --> 00:22:42,700
these planets is to test whether in fact

502
00:22:47,310 --> 00:22:45,639
you have heat redistribution from the

503
00:22:50,639 --> 00:22:47,320
day side to the night side in which case

504
00:22:52,350 --> 00:22:50,649
you would expect a more a lower

505
00:22:54,450 --> 00:22:52,360
temperature contrast from day to night

506
00:22:56,549 --> 00:22:54,460
and that would potentially indicate that

507
00:22:58,110 --> 00:22:56,559
rather than having lost over volatile as

508
00:23:02,639 --> 00:22:58,120
they might in fact still have a

509
00:23:07,889 --> 00:23:02,649
significant volatile envelope um work

510
00:23:10,680 --> 00:23:07,899
with so Edwin kite led a study taking

511
00:23:13,289 --> 00:23:10,690
this model for the silicate evaporation

512
00:23:15,659 --> 00:23:13,299
of this this melt pool and included some

513
00:23:17,639 --> 00:23:15,669

more dynamics to it so what he found was

514
00:23:20,159 --> 00:23:17,649
that you get evaporation at the subsolar

515
00:23:22,350 --> 00:23:20,169
point but in fact you get condensation

516
00:23:24,419 --> 00:23:22,360
of that material back onto the pool

517
00:23:26,610 --> 00:23:24,429
before you reach the Terminator or the

518
00:23:28,950 --> 00:23:26,620
edges of the pool and you'll get a

519
00:23:31,799 --> 00:23:28,960
dungeon a disc additional evaporation

520
00:23:33,330 --> 00:23:31,809
from out here and so in fact the regions

521
00:23:34,980 --> 00:23:33,340
where you're losing more of your mass is

522
00:23:38,460 --> 00:23:34,990
coming from the edges of the pool

523
00:23:41,759 --> 00:23:38,470
because an it can leave the boundaries

524
00:23:44,190 --> 00:23:41,769
of the pool before rican dancing and so

525
00:23:46,529 --> 00:23:44,200
you do still have this this flow of

526
00:23:49,620 --> 00:23:46,539
material coming from the dayside i'm

527
00:23:51,419 --> 00:23:49,630
sorry from the substellar point moving

528
00:23:52,710 --> 00:23:51,429
around to the night side but mantle

529
00:23:56,039 --> 00:23:52,720
convection should be sort of

530
00:24:00,149 --> 00:23:56,049
replenishing this pool from the the

531
00:24:03,240 --> 00:24:00,159
bottom of the pool the convection within

532
00:24:07,230 --> 00:24:03,250
the pool is sort of determined by the

533
00:24:09,240 --> 00:24:07,240
composition and the density evolution of

534
00:24:11,940 --> 00:24:09,250
the chemical boundary layer at the

535
00:24:14,850 --> 00:24:11,950
surface so the solid line in this figure

536
00:24:17,360 --> 00:24:14,860
is taking the evolution of that surface

537
00:24:20,580 --> 00:24:17,370
layer in calculating the density of it

538
00:24:22,860 --> 00:24:20,590

so this is the sort of residual material

539
00:24:24,629 --> 00:24:22,870
density and so you can see that this is

540
00:24:26,700 --> 00:24:24,639
for a book silicate Earth sort of

541
00:24:30,240 --> 00:24:26,710
composition which is relatively

542
00:24:32,190 --> 00:24:30,250
low in iron oxide and you get a marginal

543
00:24:34,500 --> 00:24:32,200
decrease in the density of this surface

544
00:24:37,860 --> 00:24:34,510
layer until you get out to here where

545
00:24:40,350 --> 00:24:37,870
it's initially returns back to the same

546
00:24:44,760 --> 00:24:40,360
and the highest density you get is out

547
00:24:48,080 --> 00:24:44,770
here at about 70 percent evaporated but

548
00:24:53,850 --> 00:24:48,090
what happens if you have more iron oxide

549
00:24:59,850 --> 00:24:53,860
in your in your sorry in your bulk

550
00:25:02,820 --> 00:24:59,860
composition is that the the evaporation

551
00:25:05,490 --> 00:25:02,830
of that surface layer produces material

552
00:25:07,769 --> 00:25:05,500
that is lower density and so it's

553
00:25:10,049 --> 00:25:07,779
buoyant and so this this upper layer

554
00:25:12,779 --> 00:25:10,059
remains buoyant and you never get full

555
00:25:15,870 --> 00:25:12,789
overturn of that layer and so this layer

556
00:25:17,820 --> 00:25:15,880
can evolve into becoming more calcium

557
00:25:19,769 --> 00:25:17,830
and aluminum dominated and you would

558
00:25:23,519 --> 00:25:19,779
expect these kinds of planets to have

559
00:25:25,950 --> 00:25:23,529
sort of compositionally uniform but

560
00:25:29,669 --> 00:25:25,960
evolved surfaces of this sort of

561
00:25:33,000 --> 00:25:29,679
composition for materials that have less

562
00:25:35,130 --> 00:25:33,010
iron and their bulk composition this

563
00:25:38,250 --> 00:25:35,140

fractional vaporization leads to this

564
00:25:40,909 --> 00:25:38,260
this boundary layer becoming denser over

565
00:25:43,620 --> 00:25:40,919
time and so it will eventually overturn

566
00:25:47,279 --> 00:25:43,630
and so you can get variable and patchy

567
00:25:51,779 --> 00:25:47,289
surfaces or sort of uniform surfaces

568
00:25:54,570 --> 00:25:51,789
depending on the the relative timescales

569
00:25:58,440 --> 00:25:54,580
of the chemical and the thermal over

570
00:26:00,510 --> 00:25:58,450
turn times of these planets so I think

571
00:26:01,980 --> 00:26:00,520
these planets are extremely interesting

572
00:26:04,260 --> 00:26:01,990
and I think there's a lot of interesting

573
00:26:06,019 --> 00:26:04,270
work still to be done on them in order

574
00:26:08,220 --> 00:26:06,029
to understand them better and hopefully

575
00:26:10,830 --> 00:26:08,230
observations with James Webb would be

576
00:26:12,240 --> 00:26:10,840
able to improve our understanding here

577
00:26:14,399 --> 00:26:12,250
but I think some outstanding questions

578
00:26:16,169 --> 00:26:14,409
on these planets are are these a lot of

579
00:26:16,889 --> 00:26:16,179
planets in fact completely devoid of

580
00:26:18,960 --> 00:26:16,899
volatiles

581
00:26:22,110 --> 00:26:18,970
this was sort of a starting assumption

582
00:26:24,360 --> 00:26:22,120
that we made and it hasn't really been

583
00:26:25,980 --> 00:26:24,370
tested if they have a thin volatile

584
00:26:27,810 --> 00:26:25,990
envelope that might not be

585
00:26:31,289 --> 00:26:27,820
distinguishable from the mass and radius

586
00:26:35,810 --> 00:26:31,299
of the planets but potentially it could

587
00:26:39,269 --> 00:26:35,820
be determine from secondary eclipses and

588
00:26:40,350 --> 00:26:39,279

the reason obviously that this problem

589
00:26:42,270 --> 00:26:40,360
hasn't been done be

590
00:26:44,340 --> 00:26:42,280
is because as as James Owen was telling

591
00:26:45,810 --> 00:26:44,350
us earlier these escape problems are

592
00:26:47,910 --> 00:26:45,820
pretty hard especially when you're

593
00:26:51,120 --> 00:26:47,920
talking about heavier elements and not

594
00:26:53,610 --> 00:26:51,130
just hydrogen and helium so then the

595
00:26:56,490 --> 00:26:53,620
question is how much of the if if these

596
00:26:59,039 --> 00:26:56,500
are just silicate planets how much of

597
00:27:03,270 --> 00:26:59,049
the heavy elements can evaporate from

598
00:27:05,940 --> 00:27:03,280
them can you start to lose sodium from

599
00:27:08,490 --> 00:27:05,950
your planet altogether for instance um

600
00:27:10,860 --> 00:27:08,500
and then the model here of this

601
00:27:13,080 --> 00:27:10,870
lava-like sort of assumes a synchronous

602
00:27:16,159 --> 00:27:13,090
rotation and the question is whether

603
00:27:19,620 --> 00:27:16,169
this is valid for all of these planets

604
00:27:22,860 --> 00:27:19,630
have they all fully most of them are

605
00:27:25,320 --> 00:27:22,870
likely fully tidally locked but what

606
00:27:26,669 --> 00:27:25,330
about true polar wander jeremy LeConte

607
00:27:29,070 --> 00:27:26,679
has showed that this is possible for

608
00:27:32,419 --> 00:27:29,080
planets in the habitable zone is this

609
00:27:35,190 --> 00:27:32,429
possible for these clothes and planets

610
00:27:36,659 --> 00:27:35,200
possibly not all of them but maybe a

611
00:27:38,400 --> 00:27:36,669
subset of them would not be fully

612
00:27:42,600 --> 00:27:38,410
synchronously rotating and then what are

613
00:27:46,950 --> 00:27:42,610

the implications for the surface

614
00:27:49,560 --> 00:27:46,960
environment of this planet um so now I'm

615
00:27:51,299 --> 00:27:49,570
gonna switch gears again from this and

616
00:27:53,549 --> 00:27:51,309
leave you with those open questions for

617
00:27:55,860 --> 00:27:53,559
lab of planets and go back to more

618
00:27:59,130 --> 00:27:55,870
volatile rich planets and talk about

619
00:28:02,280 --> 00:27:59,140
volatile and magma ocean of interactions

620
00:28:04,560 --> 00:28:02,290
and I like this figure for of this lava

621
00:28:06,060 --> 00:28:04,570
lake again because you have these gases

622
00:28:08,280 --> 00:28:06,070
coming out of it that's really

623
00:28:10,080 --> 00:28:08,290
emphasizing that the vocals are actually

624
00:28:12,539 --> 00:28:10,090
coming out of this lava there they're

625
00:28:15,330 --> 00:28:12,549
dissolved in the lava here and so

626
00:28:17,159 --> 00:28:15,340
there's a real interaction between lavas

627
00:28:22,470 --> 00:28:17,169
and the atmosphere in these kinds of

628
00:28:24,930 --> 00:28:22,480
systems so the water will partition as

629
00:28:27,200 --> 00:28:24,940
the magma ocean crystallizes and cools

630
00:28:29,430 --> 00:28:27,210
off between the melt and the solid

631
00:28:33,240 --> 00:28:29,440
within the Earth's mantle there's

632
00:28:34,890 --> 00:28:33,250
there's probably at least the same

633
00:28:39,120 --> 00:28:34,900
amount of water as there is on the

634
00:28:41,730 --> 00:28:39,130
surface possibly more um although that

635
00:28:44,190 --> 00:28:41,740
is still pretty highly debated this

636
00:28:45,780 --> 00:28:44,200
figure on the left is showing the

637
00:28:48,090 --> 00:28:45,790
solubility of water in different

638
00:28:50,040 --> 00:28:48,100

minerals within the Earth's mantle today

639
00:28:50,659 --> 00:28:50,050
you can see there's a region here called

640
00:28:53,119 --> 00:28:50,669
the transit

641
00:28:55,369 --> 00:28:53,129
where there's potential for a lot of

642
00:28:57,139 --> 00:28:55,379
water storage capability but it's not

643
00:29:00,440 --> 00:28:57,149
really known yet whether there is

644
00:29:03,499 --> 00:29:00,450
actually water this much water in that

645
00:29:05,629 --> 00:29:03,509
region so the water once the magma ocean

646
00:29:08,330 --> 00:29:05,639
starts to crystallize will be stored in

647
00:29:12,499 --> 00:29:08,340
these nominally anhydrous minerals like

648
00:29:14,960 --> 00:29:12,509
olivine so olivine is mg 2 SiO 4 it does

649
00:29:18,289 --> 00:29:14,970
not have water in its chemical formula

650
00:29:22,489 --> 00:29:18,299
so the water is stored in small spaces

651
00:29:25,460 --> 00:29:22,499
in the crystal lattice mostly as as Oh H

652
00:29:27,049 --> 00:29:25,470
groups um but the abundance of water

653
00:29:28,789 --> 00:29:27,059
that you can store in the olivine is

654
00:29:31,310 --> 00:29:28,799
dependent on the pressure and the depth

655
00:29:34,460 --> 00:29:31,320
within the planet in within magma ocean

656
00:29:36,049 --> 00:29:34,470
models we parameterize the way that

657
00:29:39,710 --> 00:29:36,059
water will partition between the melt

658
00:29:42,039 --> 00:29:39,720
and the solid phase by a partition

659
00:29:44,690 --> 00:29:42,049
coefficient so these are based on

660
00:29:48,080 --> 00:29:44,700
experimental measurements of how water

661
00:29:49,489 --> 00:29:48,090
will distribute itself in a system and

662
00:29:51,560 --> 00:29:49,499
so this is just the concentration of

663
00:29:53,539 --> 00:29:51,570

water in the crystal phase divided by

664
00:29:56,599 --> 00:29:53,549
the concentration in a coexisting melt

665
00:29:59,930 --> 00:29:56,609
phase and for many of the minerals found

666
00:30:02,599 --> 00:29:59,940
commonly within the earth that value is

667
00:30:04,999 --> 00:30:02,609
below one which indicates that the water

668
00:30:07,580 --> 00:30:05,009
actually wants to stay as long as it can

669
00:30:09,950 --> 00:30:07,590
in the melt phase and so what happens is

670
00:30:11,930 --> 00:30:09,960
that as the magma ocean starts to

671
00:30:15,139 --> 00:30:11,940
crystallize water will become more

672
00:30:17,989 --> 00:30:15,149
abundant in the melt phase but you will

673
00:30:22,999 --> 00:30:17,999
still always retain some amount of water

674
00:30:26,289 --> 00:30:23,009
in your solid silicate minerals this is

675
00:30:28,759 --> 00:30:26,299
showing the solubility of water and co2

676
00:30:34,430 --> 00:30:28,769
within different kinds of silicate melts

677
00:30:37,249 --> 00:30:34,440
so this is as a function of pressure for

678
00:30:39,649 --> 00:30:37,259
both of these this is water in co2 the

679
00:30:41,479 --> 00:30:39,659
solubility is somewhat dependent on the

680
00:30:44,930 --> 00:30:41,489
actual composition of the silicate

681
00:30:46,509 --> 00:30:44,940
material and so you know we take models

682
00:30:49,070 --> 00:30:46,519
for the earth and apply them to

683
00:30:51,560 --> 00:30:49,080
exoplanets but understanding the

684
00:30:53,570 --> 00:30:51,570
composition space of the solubility for

685
00:30:56,840 --> 00:30:53,580
many of these volatiles is going to be

686
00:31:00,729 --> 00:30:56,850
very important in the future

687
00:31:04,070 --> 00:31:00,739
so water is has a has a high solubility

688
00:31:06,380 --> 00:31:04,080

sio2 is is somewhat soluble but it

689
00:31:08,870 --> 00:31:06,390
actually partition more preferentially

690
00:31:11,210 --> 00:31:08,880
into the atmosphere and stay in the in

691
00:31:13,370 --> 00:31:11,220
the melt um the other thing is that

692
00:31:15,649 --> 00:31:13,380
these volatile is actually interact with

693
00:31:18,320 --> 00:31:15,659
each other within the melt phase and so

694
00:31:21,110 --> 00:31:18,330
um if you have both water and co2

695
00:31:25,009 --> 00:31:21,120
dissolved within the melt they live each

696
00:31:29,659 --> 00:31:25,019
other solubility so along an isobar here

697
00:31:32,659 --> 00:31:29,669
this is 1 kilo bar if you have 400 parts

698
00:31:36,500 --> 00:31:32,669
per million of co2 you're limited to two

699
00:31:40,310 --> 00:31:36,510
weight percent of water for instance so

700
00:31:42,049 --> 00:31:40,320
the this is because the the the ball

701
00:31:45,879 --> 00:31:42,059
tools are reacting to the the mutual

702
00:31:48,440 --> 00:31:45,889
pressure of the of the fluid the

703
00:31:51,139 --> 00:31:48,450
volatile solubility within the mount

704
00:31:53,840 --> 00:31:51,149
also depends on a factor called the

705
00:31:58,070 --> 00:31:53,850
oxidation state or the oxygen fugacity

706
00:32:00,799 --> 00:31:58,080
of the system this is a compilation of

707
00:32:03,350 --> 00:32:00,809
different volatile dissolved within

708
00:32:05,690 --> 00:32:03,360
silicate melt as a function of oxygen

709
00:32:08,600 --> 00:32:05,700
fugacity and I have a quick side here

710
00:32:11,690 --> 00:32:08,610
just to explain very quickly what oxygen

711
00:32:13,460 --> 00:32:11,700
fugacity is um within a gas phase you

712
00:32:16,009 --> 00:32:13,470
can consider oxygen fugacity just the

713
00:32:19,549 --> 00:32:16,019

partial pressure of the oxygen but

714
00:32:23,299 --> 00:32:19,559
within a solid or a liquid phase um the

715
00:32:27,350 --> 00:32:23,309
oxygen fugacity is more of a potential

716
00:32:29,840 --> 00:32:27,360
measure of the relative abundances of

717
00:32:34,370 --> 00:32:29,850
elements that have different valence

718
00:32:36,350 --> 00:32:34,380
States so that is within a silicate the

719
00:32:39,860 --> 00:32:36,360
the dominant element that is current

720
00:32:42,860 --> 00:32:39,870
controlling this is is iron so iron has

721
00:32:45,680 --> 00:32:42,870
three major valence states within a

722
00:32:47,840 --> 00:32:45,690
silicate planet that is metal which is

723
00:32:51,019 --> 00:32:47,850
found in the core predominantly there's

724
00:32:53,269 --> 00:32:51,029
iron 2 plus an iron 3 plus and so this

725
00:32:57,379 --> 00:32:53,279
valence state is determining how much

726
00:32:59,990 --> 00:32:57,389
oxygen the iron can react with so if one

727
00:33:01,850 --> 00:33:00,000
of the dominant controlling reactions

728
00:33:04,100 --> 00:33:01,860
especially during core formation is this

729
00:33:06,970 --> 00:33:04,110
iron website buffer so the presence of

730
00:33:10,639 --> 00:33:06,980
metal will limit the amount of oxygen

731
00:33:12,500 --> 00:33:10,649
Piazzi of a system but the oxygen is

732
00:33:16,549 --> 00:33:12,510
reacting with the metal and making this

733
00:33:20,000 --> 00:33:16,559
iron two-plus and the oxygen fugacity is

734
00:33:22,279 --> 00:33:20,010
within an outgassing system will also

735
00:33:25,850 --> 00:33:22,289
control the composition of the gas phase

736
00:33:28,880 --> 00:33:25,860
so the oxygen Piazzi is proportional to

737
00:33:31,970 --> 00:33:28,890
the relative abundances of say water

738
00:33:35,779 --> 00:33:31,980

vapor to hydrogen or co2 to carbon

739
00:33:39,140 --> 00:33:35,789
monoxide so to go back to this figure of

740
00:33:43,220 --> 00:33:39,150
the volatile solubilities at low oxygen

741
00:33:45,740 --> 00:33:43,230
fugacities we favor reduced forms of the

742
00:33:48,110 --> 00:33:45,750
volatiles like methane is the dominant

743
00:33:49,880 --> 00:33:48,120
form of carbon as you go to higher

744
00:33:52,279 --> 00:33:49,890
oxygen fugacity as you favor more

745
00:33:56,060 --> 00:33:52,289
oxygen-rich volatiles like carbonates

746
00:33:58,340 --> 00:33:56,070
for instance molecular hydrogen which is

747
00:34:01,310 --> 00:33:58,350
shown in this figure here is much more

748
00:34:04,430 --> 00:34:01,320
soluble in melts that have a low oxygen

749
00:34:06,830 --> 00:34:04,440
fee acity and at higher oxygen fugacity

750
00:34:10,580 --> 00:34:06,840
as you favor water as the hydrogen

751
00:34:15,139 --> 00:34:10,590
bearing species so I encourage you also

752
00:34:17,119 --> 00:34:15,149
to go look at the poster of Sakuraba who

753
00:34:22,220 --> 00:34:17,129
is looking at volatile partitioning

754
00:34:25,220 --> 00:34:22,230
during impacts on the early Earth ok and

755
00:34:27,950 --> 00:34:25,230
water also influences the melting point

756
00:34:30,260 --> 00:34:27,960
of silicates this is I showed you

757
00:34:33,649 --> 00:34:30,270
earlier a model of the solidus and

758
00:34:36,889 --> 00:34:33,659
liquidus of the magma ocean many times

759
00:34:39,829 --> 00:34:36,899
we assume a dry solidus this is where

760
00:34:41,450 --> 00:34:39,839
we're looking at the measured melting

761
00:34:43,730 --> 00:34:41,460
point of a system that didn't contain

762
00:34:46,159 --> 00:34:43,740
water but we know in fact that if you

763
00:34:47,750 --> 00:34:46,169

add water into that system you lower the

764
00:34:50,180 --> 00:34:47,760
the melting point sometimes

765
00:34:53,780 --> 00:34:50,190
substantially so these are three very

766
00:34:55,820 --> 00:34:53,790
different parameters ations for the wet

767
00:34:57,620 --> 00:34:55,830
solidus for the Earth's mantle so you

768
00:34:59,650 --> 00:34:57,630
can see that some of these would predict

769
00:35:03,050 --> 00:34:59,660
that the Earth's mantle should melt at

770
00:35:05,690 --> 00:35:03,060
two or three hundred Kelvin

771
00:35:10,130 --> 00:35:05,700
lower than you would predict if the

772
00:35:12,109 --> 00:35:10,140
mantle were dry um this can also

773
00:35:14,930 --> 00:35:12,119
influence magma ocean solidification

774
00:35:17,750 --> 00:35:14,940
times this is just a comparison of

775
00:35:20,359 --> 00:35:17,760
solidification times if we assume a dry

776
00:35:22,640 --> 00:35:20,369
solidus and this blue curve versus with

777
00:35:24,620 --> 00:35:22,650
the wet solidus in this red curve so if

778
00:35:28,490 --> 00:35:24,630
you have a large amount of water in your

779
00:35:29,720 --> 00:35:28,500
system you can potentially increase

780
00:35:31,309 --> 00:35:29,730
the amount of time it takes your

781
00:35:36,950 --> 00:35:31,319
magnetization to solidify pretty

782
00:35:38,660 --> 00:35:36,960
significantly one one thing that people

783
00:35:42,800 --> 00:35:38,670
have brought up a couple of times now is

784
00:35:44,510 --> 00:35:42,810
this idea of a fuzzy core for for giant

785
00:35:46,940 --> 00:35:44,520
planets potentially for sudden Neptune's

786
00:35:50,780 --> 00:35:46,950
and I think also for these steam

787
00:35:53,630 --> 00:35:50,790
atmosphere planets at some point water

788
00:35:56,690 --> 00:35:53,640

and rock become fully miscible within

789
00:35:58,670 --> 00:35:56,700
one another so water we know is in small

790
00:36:01,870 --> 00:35:58,680
quantities soluble in Iraq or in the

791
00:36:07,609 --> 00:36:01,880
melt at high pressures and temperatures

792
00:36:11,599 --> 00:36:07,619
the water rock mixture is is a single

793
00:36:13,940 --> 00:36:11,609
fluid so this is the phase diagram for

794
00:36:16,670 --> 00:36:13,950
the basalt water system basalts a very

795
00:36:18,859 --> 00:36:16,680
common melt on the earth this is showing

796
00:36:23,200 --> 00:36:18,869
at at pressures below this critical

797
00:36:26,510 --> 00:36:23,210
point um you have that for most of this

798
00:36:29,990 --> 00:36:26,520
phase space you have a basaltic solid

799
00:36:32,089 --> 00:36:30,000
and you have the basalt a fluid then you

800
00:36:33,800 --> 00:36:32,099
get above the melting point of the solid

801
00:36:36,349 --> 00:36:33,810
and now you have solid and melts and

802
00:36:39,290 --> 00:36:36,359
then you have a milk and you have over

803
00:36:41,120 --> 00:36:39,300
here a separate water base fluid once

804
00:36:43,790 --> 00:36:41,130
you get to higher pressures above this

805
00:36:47,030 --> 00:36:43,800
critical point now you only have one

806
00:36:49,040 --> 00:36:47,040
fluid okay and this the conditions here

807
00:36:50,359 --> 00:36:49,050
are not very extreme this is about five

808
00:36:56,800 --> 00:36:50,369
giga pascals

809
00:37:01,730 --> 00:36:56,810
and about sorry about 14 1200 1300

810
00:37:03,920 --> 00:37:01,740
degrees C so at some point within these

811
00:37:07,849 --> 00:37:03,930
exoplanet systems we may reach the point

812
00:37:10,010 --> 00:37:07,859
where we have fully miscible water in

813
00:37:13,700 --> 00:37:10,020

Rock system at high pressures within the

814
00:37:15,620 --> 00:37:13,710
interior of a part of our planet this is

815
00:37:19,309 --> 00:37:15,630
a concept we first discussed at a

816
00:37:22,940 --> 00:37:19,319
workshop back in last February February

817
00:37:28,339 --> 00:37:22,950
2018 that 10 Lichtenberg had organized

818
00:37:30,940 --> 00:37:28,349
at University of Zurich and yeah so the

819
00:37:34,520 --> 00:37:30,950
question is what is at what sort of

820
00:37:36,109 --> 00:37:34,530
envelope mass and planet mass do we have

821
00:37:37,700 --> 00:37:36,119
stopped having this sharp boundary

822
00:37:39,620 --> 00:37:37,710
between the silicate mantle and the

823
00:37:42,360 --> 00:37:39,630
envelope I think that's very interesting

824
00:37:45,030 --> 00:37:42,370
impression for future research

825
00:37:48,060 --> 00:37:45,040
um one other thing I wanted to point out

826
00:37:50,400 --> 00:37:48,070
about the silicate Mount and the effect

827
00:37:54,960 --> 00:37:50,410
that water has on it is the density of

828
00:37:55,800 --> 00:37:54,970
the melt this is a figure on the top

829
00:37:57,660 --> 00:37:55,810
left here

830
00:38:01,890 --> 00:37:57,670
I'm sorry top right here showing the

831
00:38:04,080 --> 00:38:01,900
density of a a prototype Mountain

832
00:38:06,300 --> 00:38:04,090
prototype sort of the analog for the

833
00:38:07,950 --> 00:38:06,310
Earth's mantle as a function of the

834
00:38:09,960 --> 00:38:07,960
water content so you can see is going

835
00:38:15,060 --> 00:38:09,970
from about 3.7 grams per centimeter

836
00:38:17,850 --> 00:38:15,070
cubed down to about 3.2 if you add 20

837
00:38:20,250 --> 00:38:17,860
weight percent of water into this into

838
00:38:22,350 --> 00:38:20,260

this melt this is at about 15 GPA um

839
00:38:25,080 --> 00:38:22,360
over here on the Left I've calculated

840
00:38:26,520 --> 00:38:25,090
the equation of states the densities as

841
00:38:29,430 --> 00:38:26,530
a function of pressure and comparing it

842
00:38:32,760 --> 00:38:29,440
just with the standard solid silicate

843
00:38:35,460 --> 00:38:32,770
model for that most people use for mass

844
00:38:39,390 --> 00:38:35,470
radius diagrams this which is this blue

845
00:38:43,440 --> 00:38:39,400
curve the red curve is the dry silicate

846
00:38:45,330 --> 00:38:43,450
melt and then this yellow curve is the

847
00:38:47,790 --> 00:38:45,340
hydrated silicate melt with about 5

848
00:38:51,300 --> 00:38:47,800
weight percent water and you can see

849
00:38:54,090 --> 00:38:51,310
this is affecting mostly the upper upper

850
00:38:55,440 --> 00:38:54,100
layers of the planet but that's where

851
00:38:59,190 --> 00:38:55,450
you're going to get the largest radius

852
00:39:01,320 --> 00:38:59,200
increase so potentially we are sort of

853
00:39:04,620 --> 00:39:01,330
under estimating radius for planets that

854
00:39:08,160 --> 00:39:04,630
have a magma ocean and I also recommend

855
00:39:11,940 --> 00:39:08,170
you go talk to Edwin kite about how

856
00:39:16,680 --> 00:39:11,950
hydrogen and silicate melts might affect

857
00:39:19,380 --> 00:39:16,690
the radii of sub Neptune's in terms of

858
00:39:22,020 --> 00:39:19,390
other processes going on in the magma

859
00:39:25,950 --> 00:39:22,030
ocean the degassing process is one that

860
00:39:28,650 --> 00:39:25,960
really requires a lot more study because

861
00:39:31,650 --> 00:39:28,660
it's not clear whether we have what

862
00:39:33,870 --> 00:39:31,660
model of degassing can actually be

863
00:39:36,000 --> 00:39:33,880

achieved within a magma ocean most

864
00:39:39,000 --> 00:39:36,010
models including my own assume

865
00:39:41,190 --> 00:39:39,010
continuous degassing so that's sort of

866
00:39:43,440 --> 00:39:41,200
highlighted by this upper row of figures

867
00:39:45,690 --> 00:39:43,450
here and what we assume is that the

868
00:39:48,780 --> 00:39:45,700
silicate melt at some point reaches its

869
00:39:52,050 --> 00:39:48,790
saturation point at the surface and then

870
00:39:54,380 --> 00:39:52,060
it out gasses some amount of volatile

871
00:39:56,350 --> 00:39:54,390
zin to the atmosphere to remain at that

872
00:39:59,950 --> 00:39:56,360
saturation point

873
00:40:02,770 --> 00:39:59,960
um and this is controlled sorted by the

874
00:40:06,630 --> 00:40:02,780
diffusivity of the volatile out of the

875
00:40:13,630 --> 00:40:10,720
observations of silicate melts in lavas

876
00:40:16,300 --> 00:40:13,640
on the earth and and looking at love at

877
00:40:18,100 --> 00:40:16,310
degassing suggest that some amount of

878
00:40:21,760 --> 00:40:18,110
degassing is controlled by bubble

879
00:40:23,530 --> 00:40:21,770
formation and bubble nucleation so this

880
00:40:26,070 --> 00:40:23,540
is work from Jenny sue Colley and she

881
00:40:28,750 --> 00:40:26,080
suggests that there might be in some

882
00:40:31,810 --> 00:40:28,760
situations instead of this continuous

883
00:40:34,390 --> 00:40:31,820
degassing catastrophic degassing and so

884
00:40:35,980 --> 00:40:34,400
catastrophic degassing would in order to

885
00:40:38,650 --> 00:40:35,990
nucleate your bubbles you actually

886
00:40:41,590 --> 00:40:38,660
require an oversaturation of the

887
00:40:43,180 --> 00:40:41,600
volatile within your silicate milk and

888
00:40:45,310 --> 00:40:43,190

you also require the presence of

889
00:40:47,410 --> 00:40:45,320
nucleation agents so you have to have

890
00:40:48,820 --> 00:40:47,420
some kind of crystals and sort of the

891
00:40:50,560 --> 00:40:48,830
right kind of crystals floating around

892
00:40:53,290 --> 00:40:50,570
in your silicate in order to allow

893
00:40:55,060 --> 00:40:53,300
bubbles to nucleate and then allow them

894
00:41:00,810 --> 00:40:55,070
to percolate up to the surface where

895
00:41:03,730 --> 00:41:00,820
they can be gas so the idea here is that

896
00:41:05,650 --> 00:41:03,740
there might be some hindrances to this

897
00:41:08,290 --> 00:41:05,660
happening this bubble nucleation process

898
00:41:10,930 --> 00:41:08,300
you don't get to the super saturation

899
00:41:13,750 --> 00:41:10,940
point for instance and then the

900
00:41:16,060 --> 00:41:13,760
degassing would occur very catastrophic

901
00:41:18,630 --> 00:41:16,070
ly sorted at the very end stage of the

902
00:41:23,050 --> 00:41:18,640
magma ocean when you do enrich your melt

903
00:41:26,320 --> 00:41:23,060
much more in the volatile and this would

904
00:41:27,730 --> 00:41:26,330
be by compaction of the accumulate so

905
00:41:29,230 --> 00:41:27,740
you have crystals floating in your

906
00:41:32,590 --> 00:41:29,240
liquid and the bubbles are sort of

907
00:41:35,230 --> 00:41:32,600
trapped within that that mush of

908
00:41:36,940 --> 00:41:35,240
crystals and liquid and so it's once

909
00:41:38,950 --> 00:41:36,950
those start to compact under their own

910
00:41:40,570 --> 00:41:38,960
self gravity that the bull the Bulls

911
00:41:41,380 --> 00:41:40,580
would be free to escape and so this

912
00:41:43,930 --> 00:41:41,390
might happen

913
00:41:47,140 --> 00:41:43,940

in sort of localized occurrences and

914
00:41:49,150 --> 00:41:47,150
sort of catastrophic ly at the end stage

915
00:41:50,710 --> 00:41:49,160
of magma ocean and then there's

916
00:41:52,990 --> 00:41:50,720
possibility that some planets may have

917
00:41:55,390 --> 00:41:53,000
minimal to no degassing and this is if

918
00:41:57,280 --> 00:41:55,400
they never have enough of all tools to

919
00:41:59,020 --> 00:41:57,290
reach this saturation condition for

920
00:42:01,180 --> 00:41:59,030
either that continuous or they

921
00:42:02,830 --> 00:42:01,190
catastrophic degassing so at some point

922
00:42:04,630 --> 00:42:02,840
you might have a planet with a low

923
00:42:06,640 --> 00:42:04,640
enough volatile abundance that most the

924
00:42:07,960 --> 00:42:06,650
volatiles are going to remain trapped

925
00:42:12,250 --> 00:42:07,970
within the

926
00:42:16,420 --> 00:42:12,260
interior of the planet I'm gonna skip

927
00:42:19,120 --> 00:42:16,430
the next slide for time and go and

928
00:42:21,670 --> 00:42:19,130
switch on to to looking at some of the

929
00:42:24,339 --> 00:42:21,680
actual models for these planets this is

930
00:42:26,650 --> 00:42:24,349
going back to work by keiko hamana and

931
00:42:28,660 --> 00:42:26,660
she was again looking at the two types

932
00:42:30,609 --> 00:42:28,670
of planets that you might have depending

933
00:42:31,990 --> 00:42:30,619
on the orbital period of the planet and

934
00:42:36,040 --> 00:42:32,000
so these are sort of Earth and Venus

935
00:42:38,020 --> 00:42:36,050
analogs where you have type 1 planets

936
00:42:40,359 --> 00:42:38,030
are far enough away from their star that

937
00:42:42,450 --> 00:42:40,369
the water this is again with the

938
00:42:46,900 --> 00:42:42,460

assumption of a water vapor atmosphere

939
00:42:49,810 --> 00:42:46,910
that they can cool off without losing a

940
00:42:52,630 --> 00:42:49,820
much atmosphere and eventually form an

941
00:42:54,490 --> 00:42:52,640
ocean so the cooling time scale here is

942
00:42:58,060 --> 00:42:54,500
a few million years for this earth-like

943
00:43:00,550 --> 00:42:58,070
planet and you get water collapsing out

944
00:43:02,849 --> 00:43:00,560
of the atmosphere into an ocean in

945
00:43:06,220 --> 00:43:02,859
contrast for type 2 planets like

946
00:43:07,990 --> 00:43:06,230
potentially like Venus what happens is

947
00:43:10,420 --> 00:43:08,000
that they remain in the magma ocean

948
00:43:14,380 --> 00:43:10,430
phase for a much more extended period of

949
00:43:15,880 --> 00:43:14,390
time and they have this water layer and

950
00:43:18,520 --> 00:43:15,890
their atmosphere and some of it starts

951
00:43:20,890 --> 00:43:18,530
to escape and so in Caicos models

952
00:43:23,710 --> 00:43:20,900
actually the magma ocean only eventually

953
00:43:25,780 --> 00:43:23,720
cools off because you lose enough water

954
00:43:28,390 --> 00:43:25,790
for the surface to finally start to cool

955
00:43:32,470 --> 00:43:28,400
off but there is never any condensation

956
00:43:35,140 --> 00:43:32,480
of water in these models um so James

957
00:43:37,120 --> 00:43:35,150
Owen brought this paper up in his talk

958
00:43:39,630 --> 00:43:37,130
but I'll come back to lure and Parnes

959
00:43:43,120 --> 00:43:39,640
who showed this for exoplanets for

960
00:43:45,810 --> 00:43:43,130
m-dwarf habitable zone planets they are

961
00:43:48,839 --> 00:43:45,820
looking at how the stellar radiation

962
00:43:51,070 --> 00:43:48,849
changes with with time and stellar mass

963
00:43:52,660 --> 00:43:51,080

so this is a calculation from their

964
00:43:54,880 --> 00:43:52,670
paper of the fraction of runaway

965
00:43:56,079 --> 00:43:54,890
greenhouse flux that a planet on the

966
00:43:57,820 --> 00:43:56,089
inner edge of the habitable zone

967
00:44:00,849 --> 00:43:57,830
receives over the course of its lifetime

968
00:44:03,250 --> 00:44:00,859
four stars that are sudden-like down to

969
00:44:04,900 --> 00:44:03,260
a tenth of the solar mass and so again

970
00:44:06,849 --> 00:44:04,910
this kind of planet would remain in the

971
00:44:09,160 --> 00:44:06,859
magma ocean phase if it has a runaway

972
00:44:11,620 --> 00:44:09,170
greenhouse atmosphere for most of its

973
00:44:15,760 --> 00:44:11,630
lifetime and this then leads to the

974
00:44:18,550 --> 00:44:15,770
problem of escape of the atmosphere and

975
00:44:20,109 --> 00:44:18,560
James showed this as well this is water

976
00:44:22,190 --> 00:44:20,119
loss from these planets through this

977
00:44:24,420 --> 00:44:22,200
energy

978
00:44:26,670 --> 00:44:24,430
approximation for the atmospheric escape

979
00:44:28,109 --> 00:44:26,680
where the assumption is that the water

980
00:44:30,569 --> 00:44:28,119
is photo lysing in the upper atmosphere

981
00:44:33,539 --> 00:44:30,579
and you're losing most of the hydrogen

982
00:44:36,120 --> 00:44:33,549
and some amount of the oxygen so here

983
00:44:39,960 --> 00:44:36,130
red is complete loss of one ocean mass

984
00:44:41,670 --> 00:44:39,970
of water and then the oxygen builds up

985
00:44:44,549 --> 00:44:41,680
in the atmosphere especially for these

986
00:44:48,930 --> 00:44:44,559
intermediate-mass stars you get up to

987
00:44:51,479 --> 00:44:48,940
300 bars of oxygen in the atmosphere so

988
00:44:53,819 --> 00:44:51,489

what we wanted to look at was to try a

989
00:44:56,819 --> 00:44:53,829
similar kind of model and see how

990
00:45:00,539 --> 00:44:56,829
actually the oxygen would react with the

991
00:45:01,680 --> 00:45:00,549
magma ocean itself so we originally did

992
00:45:03,569 --> 00:45:01,690
this myself

993
00:45:06,210 --> 00:45:03,579
rubbing Wordsworth's and some other

994
00:45:09,150 --> 00:45:06,220
clubbers at Harvard did this for GJ

995
00:45:11,489 --> 00:45:09,160
11:30 to be many you're probably

996
00:45:13,440 --> 00:45:11,499
familiar with this planet it's around an

997
00:45:14,640 --> 00:45:13,450
M dwarf star about point two solar

998
00:45:17,460 --> 00:45:14,650
masses

999
00:45:19,650 --> 00:45:17,470
it's very earth-like in density it's not

1000
00:45:22,559 --> 00:45:19,660
in the Hat alone it's about 400 Kelvin

1001
00:45:23,880 --> 00:45:22,569
equilibrium temperature but we wanted to

1002
00:45:25,650 --> 00:45:23,890
look at this planet and see if it were

1003
00:45:28,890 --> 00:45:25,660
possible for it to continue outgassing

1004
00:45:31,140 --> 00:45:28,900
over the course of its lifetime and

1005
00:45:32,660 --> 00:45:31,150
whether it would have some kind of

1006
00:45:35,729 --> 00:45:32,670
residual atmosphere that we could

1007
00:45:38,160 --> 00:45:35,739
observe so this is the the magma ocean

1008
00:45:40,019 --> 00:45:38,170
model just again we have water dissolved

1009
00:45:42,359 --> 00:45:40,029
in the magma in the melt

1010
00:45:44,279 --> 00:45:42,369
we're solidifying from the bottom up and

1011
00:45:45,930 --> 00:45:44,289
we have this atmosphere that's the

1012
00:45:48,210 --> 00:45:45,940
pressure of this atmosphere is set by

1013
00:45:50,370 --> 00:45:48,220

this continuous degassing limit where

1014
00:45:52,920 --> 00:45:50,380
we're we're at solubility I sorry

1015
00:45:54,710 --> 00:45:52,930
saturation at the surface um and we have

1016
00:45:57,239 --> 00:45:54,720
X UV radiation hitting the atmosphere

1017
00:46:01,349 --> 00:45:57,249
and we're assuming the sort of energy

1018
00:46:02,999 --> 00:46:01,359
limited escape formula and so we

1019
00:46:06,059 --> 00:46:03,009
compared results for two different

1020
00:46:09,450 --> 00:46:06,069
models for the XUV flex evolution of the

1021
00:46:12,599 --> 00:46:09,460
m dwarf in and for James we used an

1022
00:46:15,150 --> 00:46:12,609
efficiency factor of 0.3 so maybe a

1023
00:46:17,099 --> 00:46:15,160
little high and then we looked at a

1024
00:46:19,710 --> 00:46:17,109
range at the results for a range of

1025
00:46:21,960 --> 00:46:19,720
initial water abundances for the planet

1026
00:46:24,599 --> 00:46:21,970
and iron oxide abundances for the mantle

1027
00:46:27,150 --> 00:46:24,609
and this is where the oxygen is reacting

1028
00:46:30,779 --> 00:46:27,160
out of the atmosphere and into the

1029
00:46:32,370 --> 00:46:30,789
planetary mantle and also highlight

1030
00:46:34,120 --> 00:46:32,380
Robyn Wordsworth is going to talk about

1031
00:46:37,809 --> 00:46:34,130
a further development of this mod

1032
00:46:39,970 --> 00:46:37,819
four habitable zone planets tomorrow so

1033
00:46:44,019 --> 00:46:39,980
this is just a quick example of a magma

1034
00:46:47,200 --> 00:46:44,029
ocean evolution calculation where we're

1035
00:46:50,160 --> 00:46:47,210
modeling the thermal structure of the

1036
00:46:53,380 --> 00:46:50,170
planet how it cools over its lifetime

1037
00:46:55,450 --> 00:46:53,390
the magma ocean is effectively over when

1038
00:46:58,690 --> 00:46:55,460

the so this is the surface temperature

1039
00:47:01,480 --> 00:46:58,700
in the mantle temperature diverge and

1040
00:47:03,339 --> 00:47:01,490
here we get a solid surface and so we no

1041
00:47:05,859 --> 00:47:03,349
longer have atmosphere and mantle

1042
00:47:08,490 --> 00:47:05,869
exchange going on this bottom figure is

1043
00:47:11,799 --> 00:47:08,500
showing the evolution of the water

1044
00:47:13,960 --> 00:47:11,809
inventory between the magma ocean which

1045
00:47:16,960 --> 00:47:13,970
is here the atmosphere in this dash line

1046
00:47:18,579 --> 00:47:16,970
and the dotted line is within the solid

1047
00:47:20,170 --> 00:47:18,589
mantle so you can see we always have

1048
00:47:24,779 --> 00:47:20,180
some amount of water remaining within

1049
00:47:27,999 --> 00:47:24,789
the mantle interior so the magma ocean

1050
00:47:29,680 --> 00:47:28,009
lifetime depends very strongly than on

1051
00:47:35,170 --> 00:47:29,690
the initial water abundance for the

1052
00:47:38,279 --> 00:47:35,180
planet this is going from yeah a few few

1053
00:47:41,950 --> 00:47:38,289
million years out to a few billion years

1054
00:47:44,470 --> 00:47:41,960
depending on the also the XUV flux so

1055
00:47:49,289 --> 00:47:44,480
again this planet often can only cool

1056
00:47:52,839 --> 00:47:49,299
off if it loses all of its water this

1057
00:47:54,640 --> 00:47:52,849
this is highlighting sort of the range

1058
00:47:56,470 --> 00:47:54,650
of lifetimes that we expect for the

1059
00:48:01,150 --> 00:47:56,480
Earth's magma ocean and the Earth's

1060
00:48:03,370 --> 00:48:01,160
water abundance and this is the amount

1061
00:48:05,230 --> 00:48:03,380
of water that the planet is left with at

1062
00:48:07,420 --> 00:48:05,240
the end of these simulations so these

1063
00:48:12,039 --> 00:48:07,430

are five billion years long again this

1064
00:48:14,140 --> 00:48:12,049
is the initial bulk water abundance and

1065
00:48:16,329 --> 00:48:14,150
this is the fraction of water that is

1066
00:48:19,720 --> 00:48:16,339
lost from the planet depending on these

1067
00:48:22,029 --> 00:48:19,730
XUV models so the pink indicates that

1068
00:48:24,190 --> 00:48:22,039
for this low xev model we actually have

1069
00:48:25,900 --> 00:48:24,200
a fair amount of water left within the

1070
00:48:29,380 --> 00:48:25,910
planet but it's all trapped within the

1071
00:48:32,109 --> 00:48:29,390
mantle as I'll show you here okay so

1072
00:48:34,120 --> 00:48:32,119
that's again the Earth's water i'mso

1073
00:48:35,980 --> 00:48:34,130
then to go to the oxygen the oxygen is

1074
00:48:37,809 --> 00:48:35,990
taken up in the magma ocean again by

1075
00:48:40,329 --> 00:48:37,819
reaction with iron because it's the

1076
00:48:42,099 --> 00:48:40,339
dominant element that has this multiple

1077
00:48:44,410 --> 00:48:42,109
valence states within the silicate melt

1078
00:48:46,779 --> 00:48:44,420
often we think in magma ocean models

1079
00:48:47,850 --> 00:48:46,789
that we're starting only with the iron

1080
00:48:50,820 --> 00:48:47,860
two plus four

1081
00:48:53,580 --> 00:48:50,830
and so here we we set the initial iron

1082
00:48:56,010 --> 00:48:53,590
three-plus to zero and allow reaction as

1083
00:48:57,780 --> 00:48:56,020
the oxygen diffuses back down through

1084
00:49:03,510 --> 00:48:57,790
the atmosphere with the melt to make

1085
00:49:06,810 --> 00:49:03,520
this this iron three-plus form um and

1086
00:49:08,400 --> 00:49:06,820
here are the results for the atmospheric

1087
00:49:11,490 --> 00:49:08,410
oxygen um buttons at the end of this

1088
00:49:14,190 --> 00:49:11,500

five billion year evolution timeline so

1089
00:49:17,490 --> 00:49:14,200
this is showing the high xev and low XUV

1090
00:49:20,250 --> 00:49:17,500
models this is for iron oxide in the

1091
00:49:24,240 --> 00:49:20,260
planets mantle and the initial water

1092
00:49:25,980 --> 00:49:24,250
abundance so for this high exiting model

1093
00:49:27,720 --> 00:49:25,990
we essentially end up with with really

1094
00:49:29,820 --> 00:49:27,730
no atmosphere left on this planet we

1095
00:49:32,280 --> 00:49:29,830
would if we go out and observe it we

1096
00:49:34,950 --> 00:49:32,290
might expect to find a Barrett Rock if

1097
00:49:37,830 --> 00:49:34,960
the atmospheric evolution has slightly

1098
00:49:40,260 --> 00:49:37,840
lower XUV and then we might expect sort

1099
00:49:42,360 --> 00:49:40,270
of a tenuous oxygen atmosphere and there

1100
00:49:43,950 --> 00:49:42,370
is still water on this planet but it's

1101
00:49:47,670 --> 00:49:43,960
trapped in the interior so there might

1102
00:49:51,630 --> 00:49:47,680
be some slow leaky outgassing coming

1103
00:49:52,950 --> 00:49:51,640
from the planets interior I'm at higher

1104
00:49:56,330 --> 00:49:52,960
water abundance as we get sort of

1105
00:49:59,730 --> 00:49:56,340
moderate oxygen levels of a few bars

1106
00:50:01,710 --> 00:49:59,740
again no real high no real water left

1107
00:50:03,900 --> 00:50:01,720
but if you go up to these sort of

1108
00:50:06,570 --> 00:50:03,910
extreme water initial water abundances

1109
00:50:08,400 --> 00:50:06,580
of ten to twenty weight percent which

1110
00:50:10,050 --> 00:50:08,410
might be above the limit where the model

1111
00:50:12,180 --> 00:50:10,060
starts breaking down you see you retain

1112
00:50:15,450 --> 00:50:12,190
this thick water atmosphere you have

1113
00:50:17,160 --> 00:50:15,460

several killer bars of oxygen and the

1114
00:50:19,170 --> 00:50:17,170
atmosphere and these planets are still

1115
00:50:21,870 --> 00:50:19,180
in this magma ocean stage because they

1116
00:50:25,880 --> 00:50:21,880
haven't cooled off and they can't cool

1117
00:50:29,280 --> 00:50:25,890
off because they have too much water um

1118
00:50:31,380 --> 00:50:29,290
if we look at the at what happens to the

1119
00:50:34,020 --> 00:50:31,390
action for these planets actually most

1120
00:50:37,110 --> 00:50:34,030
of the oxygen escapes so this is showing

1121
00:50:39,570 --> 00:50:37,120
the fraction of oxygen that remains that

1122
00:50:42,390 --> 00:50:39,580
actually reacts with the mantle of the

1123
00:50:46,110 --> 00:50:42,400
planets again this is the water and iron

1124
00:50:49,770 --> 00:50:46,120
in the mantle the color here is the

1125
00:50:51,450 --> 00:50:49,780
fraction in percent of the total oxygen

1126
00:50:53,550 --> 00:50:51,460
remaining so this is about eight to ten

1127
00:50:55,680 --> 00:50:53,560
percent of the oxygen remains within the

1128
00:50:57,960 --> 00:50:55,690
mantle and this is for the low xeb model

1129
00:51:01,200 --> 00:50:57,970
for the high XUV model in fact almost

1130
00:51:04,589 --> 00:51:01,210
all of the oxygen escape escapes

1131
00:51:07,410 --> 00:51:04,599
but as as james owen mentioned the

1132
00:51:10,859 --> 00:51:07,420
oxygen might in fact be a coolant in

1133
00:51:13,380 --> 00:51:10,869
this outflow and so so it's not clear

1134
00:51:15,390 --> 00:51:13,390
exactly how well this energy limited

1135
00:51:18,960 --> 00:51:15,400
formula for the oxygen escape is working

1136
00:51:21,829 --> 00:51:18,970
so everything limit the oxygen loss so

1137
00:51:24,990 --> 00:51:21,839
we turn it off and run the model again

1138
00:51:26,970 --> 00:51:25,000

then what we get is that in fact most of

1139
00:51:29,430 --> 00:51:26,980
the oxygen reacts with the planet's

1140
00:51:32,400 --> 00:51:29,440
mantle this is up to ninety percent is

1141
00:51:34,589 --> 00:51:32,410
reacting and this dividing line here is

1142
00:51:36,720 --> 00:51:34,599
essentially because well we have too

1143
00:51:39,000 --> 00:51:36,730
much oxygen being produced from this

1144
00:51:40,770 --> 00:51:39,010
water and the mantle can't hold on to it

1145
00:51:45,859 --> 00:51:40,780
it doesn't have enough iron oxide down

1146
00:51:49,770 --> 00:51:45,869
at this lower sorry upper left-hand side

1147
00:51:51,900 --> 00:51:49,780
so we have more mantle oxidation when

1148
00:51:57,059 --> 00:51:51,910
there is no oxygen loss up to ninety

1149
00:51:59,700 --> 00:51:57,069
percent okay and then that leaves me

1150
00:52:02,069 --> 00:51:59,710
very quickly to talk a little bit about

1151
00:52:06,780 --> 00:52:02,079
the evolution of the Earth's mantle

1152
00:52:09,809 --> 00:52:06,790
oxidation state so the we can measure

1153
00:52:11,819 --> 00:52:09,819
the Earth's oxidation state both at the

1154
00:52:14,010 --> 00:52:11,829
present day through looking at basalts

1155
00:52:18,150 --> 00:52:14,020
and other material coming out of the

1156
00:52:20,039 --> 00:52:18,160
mantle and we get values around around

1157
00:52:22,380 --> 00:52:20,049
this quartz feel like magnetite buffer

1158
00:52:23,819 --> 00:52:22,390
which is quite a bit above the iron

1159
00:52:26,099 --> 00:52:23,829
phosphate buffer that I talked about a

1160
00:52:28,349 --> 00:52:26,109
little bit before um and we have

1161
00:52:30,839 --> 00:52:28,359
measurements of proxies going back to

1162
00:52:33,150 --> 00:52:30,849
about 3.8 billion years which is sort of

1163
00:52:35,430 --> 00:52:33,160

the limit of our rock record and it

1164
00:52:37,829 --> 00:52:35,440
seems to have a pretty constant value

1165
00:52:39,990 --> 00:52:37,839
and so people have have long assumed

1166
00:52:41,849 --> 00:52:40,000
that the composition of volcanic gases

1167
00:52:44,280 --> 00:52:41,859
coming out of the Earth's interior has

1168
00:52:46,170 --> 00:52:44,290
been essentially the same over geologic

1169
00:52:49,440 --> 00:52:46,180
history because of this constant

1170
00:52:50,970 --> 00:52:49,450
oxidation state during during planet

1171
00:52:52,650 --> 00:52:50,980
formation however when there is metal

1172
00:52:56,039 --> 00:52:52,660
present and reacting with the magma

1173
00:52:58,829 --> 00:52:56,049
ocean and reacting with the silicate

1174
00:53:02,640 --> 00:52:58,839
mantle the predicted oxidation state of

1175
00:53:04,410 --> 00:53:02,650
the earth is down here it's 8 log units

1176
00:53:09,250 --> 00:53:04,420
below the present-day

1177
00:53:12,310 --> 00:53:09,260
or down to eight log units and so I'm

1178
00:53:14,530 --> 00:53:12,320
there have been a lot of people a lot of

1179
00:53:17,320 --> 00:53:14,540
models to try to explain this over time

1180
00:53:20,770 --> 00:53:17,330
through various mechanisms by accretion

1181
00:53:23,490 --> 00:53:20,780
of oxidized material by a slow oxidation

1182
00:53:26,200 --> 00:53:23,500
of hydrogen loss maybe have very slow

1183
00:53:28,090 --> 00:53:26,210
change in oxidation state over this

1184
00:53:31,620 --> 00:53:28,100
first half a million half a billion

1185
00:53:35,190 --> 00:53:31,630
years but I'm gonna talk you through

1186
00:53:38,140 --> 00:53:35,200
very quickly a possible oxidation

1187
00:53:41,260 --> 00:53:38,150
mechanism that's related solely to the

1188
00:53:42,430 --> 00:53:41,270

chemistry of the silicate melt and then

1189
00:53:45,250 --> 00:53:42,440
I'm not going to talk about this

1190
00:53:47,440 --> 00:53:45,260
actually because I won't have time so

1191
00:53:50,260 --> 00:53:47,450
this is a processes that happens during

1192
00:53:52,930 --> 00:53:50,270
core formation and it should be pretty

1193
00:53:54,790 --> 00:53:52,940
intrinsic to the process for many

1194
00:53:57,550 --> 00:53:54,800
terrestrial planets and what happens is

1195
00:53:59,470 --> 00:53:57,560
so we have both silicate and metal being

1196
00:54:03,340 --> 00:53:59,480
delivered to the planet at is as it's

1197
00:54:04,960 --> 00:54:03,350
growing and we have some equilibration

1198
00:54:06,460 --> 00:54:04,970
going on between the silicate in the

1199
00:54:08,920 --> 00:54:06,470
metal in fact we think that there is

1200
00:54:11,560 --> 00:54:08,930
some amount of silicon and oxygen

1201
00:54:13,150 --> 00:54:11,570
present within the Earth's core today

1202
00:54:15,190 --> 00:54:13,160
and that's because the density of

1203
00:54:18,970 --> 00:54:15,200
Earth's core is slightly below that of

1204
00:54:20,710 --> 00:54:18,980
pure iron and which is why I'm including

1205
00:54:23,080 --> 00:54:20,720
these reactions here so we have iron

1206
00:54:25,960 --> 00:54:23,090
metal reacting with silicates in the in

1207
00:54:28,030 --> 00:54:25,970
the liquid and you get some amount of

1208
00:54:30,310 --> 00:54:28,040
silicon and some amount of oxygen going

1209
00:54:31,960 --> 00:54:30,320
into your metal phase that is then

1210
00:54:35,140 --> 00:54:31,970
sinking to the bottom of your planet and

1211
00:54:37,630 --> 00:54:35,150
forming your metallic core and that's

1212
00:54:40,410 --> 00:54:37,640
governed by these equilibrium constants

1213
00:54:43,000 --> 00:54:40,420

over here here's a very complicated

1214
00:54:46,000 --> 00:54:43,010
formula for this from that has been

1215
00:54:48,090 --> 00:54:46,010
calibrated from experiments and then the

1216
00:54:50,550 --> 00:54:48,100
other reaction we can add into this now

1217
00:54:53,410 --> 00:54:50,560
because we now have some new

1218
00:54:55,540 --> 00:54:53,420
experimental data on silicate melts at

1219
00:54:58,540 --> 00:54:55,550
higher pressures is this reaction down

1220
00:55:02,770 --> 00:54:58,550
here at the bottom so what this reaction

1221
00:55:06,190 --> 00:55:02,780
is showing is that we have the mantle is

1222
00:55:08,590 --> 00:55:06,200
dominated by this iron two-plus in the

1223
00:55:10,810 --> 00:55:08,600
in the silicate melt but at high

1224
00:55:13,690 --> 00:55:10,820
pressure what happens is the volume

1225
00:55:16,270 --> 00:55:13,700
change of this reaction shifts in favor

1226
00:55:19,500 --> 00:55:16,280
of iron three-plus so at high pressures

1227
00:55:21,840 --> 00:55:19,510
iron three-plus becomes stabilized

1228
00:55:24,090 --> 00:55:21,850
and in order to charge balance this

1229
00:55:26,820 --> 00:55:24,100
reaction you have to also produce some

1230
00:55:28,950 --> 00:55:26,830
metal so this is kind of complicated but

1231
00:55:31,410 --> 00:55:28,960
what happens is if you can separate this

1232
00:55:33,359 --> 00:55:31,420
metal at the time that this reaction is

1233
00:55:35,849 --> 00:55:33,369
happening remove it from your mantle

1234
00:55:38,220 --> 00:55:35,859
system now you've effectively increased

1235
00:55:40,260 --> 00:55:38,230
your iron to oxygen ratio in the mantle

1236
00:55:42,270 --> 00:55:40,270
and this is connected of course to

1237
00:55:44,820 --> 00:55:42,280
outgassing through the oxygen fugacity

1238
00:55:47,760 --> 00:55:44,830

of the system so the higher the iron

1239
00:55:50,849 --> 00:55:47,770
three-plus abundance the higher your

1240
00:55:53,510 --> 00:55:50,859
oxygen fugacity is going to be so we've

1241
00:55:56,960 --> 00:55:53,520
done some calculations using some newer

1242
00:55:58,980 --> 00:55:56,970
experimental data on this prior

1243
00:56:01,710 --> 00:55:58,990
calculations would put the iron

1244
00:56:04,260 --> 00:56:01,720
three-plus abundance within the silicate

1245
00:56:06,570 --> 00:56:04,270
melt at as a function of pressure along

1246
00:56:08,250 --> 00:56:06,580
this green curve here and so core

1247
00:56:10,830 --> 00:56:08,260
information we think happens at pretty

1248
00:56:13,170 --> 00:56:10,840
high pressures up to 50 to 60 Giga

1249
00:56:14,670 --> 00:56:13,180
Pascal's within the planet and that

1250
00:56:18,090 --> 00:56:14,680
pressure should probably grow as a

1251
00:56:20,820 --> 00:56:18,100
function of planet size but so this

1252
00:56:23,010 --> 00:56:20,830
original low pressure data would suggest

1253
00:56:25,460 --> 00:56:23,020
that you don't really produce any of

1254
00:56:28,950 --> 00:56:25,470
this iron three-plus in the mantle um

1255
00:56:31,200 --> 00:56:28,960
but this new experimental data gives us

1256
00:56:33,390 --> 00:56:31,210
this curve up here which at the

1257
00:56:35,130 --> 00:56:33,400
conditions that we think for the average

1258
00:56:37,590 --> 00:56:35,140
core formation conditions of the Earth's

1259
00:56:39,599 --> 00:56:37,600
gives us about one-and-a-half percent of

1260
00:56:44,460 --> 00:56:39,609
iron three-plus and that matches the

1261
00:56:46,320 --> 00:56:44,470
present-day so with this new data we can

1262
00:56:48,349 --> 00:56:46,330
now match the oxidation state of the

1263
00:56:51,780 --> 00:56:48,359

Earth's mantle

1264
00:56:53,910 --> 00:56:51,790
during core information so I'm gonna

1265
00:56:58,730 --> 00:56:53,920
skip through a lot of this because it's

1266
00:57:02,130 --> 00:56:58,740
complicated but what happens is is that

1267
00:57:04,380 --> 00:57:02,140
you have during this time of core

1268
00:57:06,240 --> 00:57:04,390
formation you have a really low oxygen

1269
00:57:09,750 --> 00:57:06,250
fugacity and so you expect really

1270
00:57:11,640 --> 00:57:09,760
reduced gases like hydrogen h2 and

1271
00:57:14,370 --> 00:57:11,650
carbon monoxide to be your outgassing

1272
00:57:16,349 --> 00:57:14,380
species as you increase the oxidation

1273
00:57:18,300 --> 00:57:16,359
state of the mantle you should expect a

1274
00:57:21,870 --> 00:57:18,310
shift from that kind of composition to

1275
00:57:25,920 --> 00:57:21,880
more water and co2 rich atmospheres and

1276
00:57:29,580 --> 00:57:25,930
so because this reaction is a function

1277
00:57:31,590 --> 00:57:29,590
of pressure of this of this reaction it

1278
00:57:32,089 --> 00:57:31,600
might be a function of planet size as

1279
00:57:34,699 --> 00:57:32,099
well

1280
00:57:36,859 --> 00:57:34,709
and so you might expect a shift in the

1281
00:57:39,140 --> 00:57:36,869
oxidation state from smaller planets

1282
00:57:46,039 --> 00:57:39,150
being more reduced to the larger planets

1283
00:57:52,519 --> 00:57:46,049
being more oxidized okay okay so I'll

1284
00:57:55,189 --> 00:57:52,529
just skip really quickly from that so so

1285
00:57:57,079 --> 00:57:55,199
by the time our planet is fully formed

1286
00:57:59,299 --> 00:57:57,089
we should be at an oxidation state for

1287
00:58:04,459 --> 00:57:59,309
the earth at least where we favor water

1288
00:58:05,959 --> 00:58:04,469

and co2 compositions but this is a

1289
00:58:07,519 --> 00:58:05,969
calculation that we did for the book

1290
00:58:09,229 --> 00:58:07,529
silicate earth where you can see that

1291
00:58:11,599 --> 00:58:09,239
it's not just water and co2 in this

1292
00:58:14,420 --> 00:58:11,609
atmosphere there's a lot more minor

1293
00:58:17,359 --> 00:58:14,430
species like sulphur dioxide you have a

1294
00:58:19,130 --> 00:58:17,369
lot of lots of file elements and these

1295
00:58:20,689 --> 00:58:19,140
are all contributing to the spectra

1296
00:58:22,430 --> 00:58:20,699
they're contributing to the rate at

1297
00:58:25,160 --> 00:58:22,440
which the planet is cooling from the

1298
00:58:27,229 --> 00:58:25,170
upper atmosphere this is a calculation

1299
00:58:29,900 --> 00:58:27,239
of the emission spectra of the top of

1300
00:58:33,589 --> 00:58:29,910
the atmosphere that Roxanna looper did

1301
00:58:36,349 --> 00:58:33,599
with these gas compositions compared to

1302
00:58:40,400 --> 00:58:36,359
models of pure waters sorry this is a

1303
00:58:42,469 --> 00:58:40,410
model of 90% water and 10% co2 so that

1304
00:58:46,870 --> 00:58:42,479
composition on the previous page is in

1305
00:58:49,279 --> 00:58:46,880
the red the blue is another complicated

1306
00:58:51,229 --> 00:58:49,289
continental crust composition and you

1307
00:58:53,839 --> 00:58:51,239
can see a significant difference in the

1308
00:58:56,239 --> 00:58:53,849
spectra of this planet this could be

1309
00:58:58,599 --> 00:58:56,249
observable in for instance giant impacts

1310
00:59:01,339 --> 00:58:58,609
this could be observable in these hot

1311
00:59:03,400 --> 00:59:01,349
exoplanets that have surface magma

1312
00:59:06,049 --> 00:59:03,410
oceans caused by the steam atmosphere

1313
00:59:09,349 --> 00:59:06,059

but it also affects the cooling time

1314
00:59:11,539 --> 00:59:09,359
scale for for Earth in particular

1315
00:59:13,999 --> 00:59:11,549
so I'll just bump through this really

1316
00:59:16,519 --> 00:59:14,009
quickly this is the cooling timescale if

1317
00:59:18,769 --> 00:59:16,529
you take that continental crust derived

1318
00:59:20,359 --> 00:59:18,779
atmosphere you get a cooling timescale

1319
00:59:23,660 --> 00:59:20,369
for the Earth's magma ocean of about

1320
00:59:25,549 --> 00:59:23,670
200,000 years for that bulk silicate

1321
00:59:28,099 --> 00:59:25,559
Earth composition you get two million

1322
00:59:32,299 --> 00:59:28,109
years so that's a factor of 10 in

1323
00:59:36,589 --> 00:59:32,309
cooling timescale okay so with that I am

1324
00:59:39,079 --> 00:59:36,599
going to jump to my conclusion slide and

1325
00:59:40,339 --> 00:59:39,089
I'll tell you I think one of the big

1326
00:59:42,769 --> 00:59:40,349
things to take away from this is that

1327
00:59:44,449 --> 00:59:42,779
the planetary oxidation state is

1328
00:59:45,650 --> 00:59:44,459
determined during the magma ocean stage

1329
00:59:48,320 --> 00:59:45,660
for many plain

1330
00:59:51,320 --> 00:59:48,330
it might be a function of the planet

1331
00:59:53,180 --> 00:59:51,330
sighs I think we really need some

1332
00:59:55,250 --> 00:59:53,190
improved models to understand the

1333
00:59:57,560 --> 00:59:55,260
evolution of oxidation state for both

1334
00:59:59,090 --> 00:59:57,570
Earth's and other planets and then I

1335
01:00:01,400 --> 00:59:59,100
think there's a lot of interesting

1336
01:00:03,380 --> 01:00:01,410
outstanding issues to work on for the

1337
01:00:05,300 --> 01:00:03,390
lava worlds whether they have volatile

1338
01:00:07,730 --> 01:00:05,310

x' or not whether they're synchronously

1339
01:00:10,010 --> 01:00:07,740
rotating the runaway greenhouse planets

1340
01:00:13,000 --> 01:00:10,020
and what their atmospheric compositions

1341
01:00:15,530 --> 01:00:13,010
are what their spectra are and whether

1342
01:00:17,960 --> 01:00:15,540
atmospheric escape is sculpting their

1343
01:00:20,360 --> 01:00:17,970
compositions and then we need a lot of

1344
01:00:22,070 --> 01:00:20,370
experimental data so if you're inspired

1345
01:00:23,570 --> 01:00:22,080
by Maggie's talk earlier and want to get

1346
01:00:25,940 --> 01:00:23,580
into experiments there's plenty of

1347
01:00:35,990 --> 01:00:25,950
things to measure okay so with that

1348
01:00:38,150 --> 01:00:36,000
thank you okay we covered a lot of

1349
01:00:50,440 --> 01:00:38,160
ground but we have a question for time

1350
01:00:56,360 --> 01:00:54,560
thanks for a great talk this might be

1351
01:01:00,590 --> 01:00:56,370
very naive question but at the very

1352
01:01:04,490 --> 01:01:00,600
lower planet size regime is there any

1353
01:01:08,870 --> 01:01:04,500
evidence the mercury love oceans and or

1354
01:01:12,050 --> 01:01:08,880
outgassing and could any constraints on

1355
01:01:14,300 --> 01:01:12,060
that be used to to help inform the

1356
01:01:18,380 --> 01:01:14,310
interior cooling rate models for that

1357
01:01:19,970 --> 01:01:18,390
very low size right right so there there

1358
01:01:22,670 --> 01:01:19,980
has been obviously suggestions that

1359
01:01:24,440 --> 01:01:22,680
mercury lost a lot of its mantle due to

1360
01:01:26,480 --> 01:01:24,450
a giant impact and then you would assume

1361
01:01:28,730 --> 01:01:26,490
that some portion of the the remaining

1362
01:01:30,530 --> 01:01:28,740
planet might have melted as well um we

1363
01:01:33,410 --> 01:01:30,540

don't have really good evidence from the

1364
01:01:37,700 --> 01:01:33,420
the present set of observations for a

1365
01:01:46,520 --> 01:01:37,710
magma ocean but you know Steve - he has

1366
01:01:55,550 --> 01:01:46,530
a model does anyone have a burning

1367
01:01:59,550 --> 01:01:57,180
great talk

1368
01:02:01,830 --> 01:01:59,560
Ted c'mon sake Chicago so a couple

1369
01:02:04,980 --> 01:02:01,840
people in this room a couple years ago

1370
01:02:07,590 --> 01:02:04,990
tried to explain 55 canker ease thermal

1371
01:02:10,830 --> 01:02:07,600
phase curve using a hydrogen nitrogen

1372
01:02:12,750 --> 01:02:10,840
atmosphere is that like is that okay if

1373
01:02:16,650 --> 01:02:12,760
there's a magma ocean a lava lava ocean

1374
01:02:18,450 --> 01:02:16,660
or is that not okay chemically um I mean

1375
01:02:19,920 --> 01:02:18,460
I think you'd you could definitely still

1376
01:02:22,830 --> 01:02:19,930
have a magma ocean with a hydrogen

1377
01:02:26,340 --> 01:02:22,840
nitrogen atmosphere I think the question

1378
01:02:29,370 --> 01:02:26,350
for me is whether a hydrogen atmosphere

1379
01:02:31,680 --> 01:02:29,380
is stable against the escape certainly I

1380
01:02:33,780 --> 01:02:31,690
think that planet has to have some kind

1381
01:02:40,650 --> 01:02:33,790
of atmosphere to explain it's it's lower

1382
01:02:42,210 --> 01:02:40,660
density yeah yeah I'll just comment as

1383
01:02:44,550 --> 01:02:42,220
we said as Mark and I said in the paper

1384
01:02:46,770 --> 01:02:44,560
we don't think that a hydrogen

1385
01:02:50,550 --> 01:02:46,780
atmosphere is actually plausible because

1386
01:02:53,940 --> 01:02:50,560
of the escape problem but if you really

1387
01:02:56,400 --> 01:02:53,950
believe the phase shift of the hotspot

1388
01:02:57,960 --> 01:02:56,410

that forces you in the direction of a

1389
01:03:00,510 --> 01:02:57,970
hydrogen a hydrogen rich atmosphere

1390
01:03:03,300 --> 01:03:00,520
which is really problematic right right

1391
01:03:04,350 --> 01:03:03,310
and in order to account for the HCN

1392
01:03:06,240 --> 01:03:04,360
observation if you believe that

1393
01:03:08,970 --> 01:03:06,250
observation is hard to do that without

1394
01:03:12,990 --> 01:03:08,980
some significant hydrogen bearing