Is our Milky Way Teeming with Intelligent Life ?

- 20 Billion Planetary Systems:
  → 1/2 are older than Earth
- What fraction have Intelligent Life?
- Pessimist: 1 in a Million

There must be Thousands of Advanced Civilizations In the Milky Way Galaxy. . .

1
00:00:03,190 --> 00:00:02,310
good morning

2
00:00:05,190 --> 00:00:03,200
uh

3
00:00:07,829 --> 00:00:05,200
i'd like to welcome you all to the

4
00:00:09,990 --> 00:00:07,839
latest in the director seminar series

5
00:00:12,070 --> 00:00:10,000
for the nasa astrobiology institute

6
00:00:16,390 --> 00:00:12,080
we're broadcasting to you this morning

7
00:00:18,710 --> 00:00:16,400
from the exoplanet division here at nai

8
00:00:23,509 --> 00:00:18,720
and we are really really pleased to have

9
00:00:25,349 --> 00:00:23,519
jeff marcy uh the discoverer of uh most

10
00:00:27,269 --> 00:00:25,359
or the leader of the team uh that

11
00:00:29,750 --> 00:00:27,279
discovered most of the planets that we

12
00:00:30,950 --> 00:00:29,760
know about around other stars with us

13
00:00:33,990 --> 00:00:30,960

this morning

14
00:00:36,950 --> 00:00:34,000
jeff has had a distinguished career

15
00:00:39,910 --> 00:00:36,960
which certainly began in california with

16
00:00:43,030 --> 00:00:39,920
degrees from ucla and phd in astronomy

17
00:00:45,030 --> 00:00:43,040
and astrophysics from uc santa cruz uh

18
00:00:46,869 --> 00:00:45,040
then went back east to the carnegie

19
00:00:48,790 --> 00:00:46,879
institution for a while

20
00:00:50,950 --> 00:00:48,800
and then came back to california and has

21
00:00:55,350 --> 00:00:50,960
been a professor at san francisco state

22
00:00:58,389 --> 00:00:55,360
university and now at uc berkeley

23
00:01:00,950 --> 00:00:58,399
he is going to be talking to us this

24
00:01:03,830 --> 00:01:00,960
morning about getting to the core of

25
00:01:11,350 --> 00:01:03,840
exoplanets from gas to ice giants and i

26
00:01:14,950 --> 00:01:12,630
uh let's see

27
00:01:17,830 --> 00:01:14,960
it's a pleasure to be here um

28
00:01:19,910 --> 00:01:17,840
this is an exciting venue to be able to

29
00:01:22,310 --> 00:01:19,920
describe some of the recent results in

30
00:01:24,630 --> 00:01:22,320
extrasolar climates to a wide variety of

31
00:01:27,109 --> 00:01:24,640
people that have interests that are

32
00:01:28,870 --> 00:01:27,119
more diverse certainly than the planets

33
00:01:31,030 --> 00:01:28,880
themselves offer

34
00:01:32,390 --> 00:01:31,040
let me just say that i'm going to try

35
00:01:34,149 --> 00:01:32,400
today to

36
00:01:36,950 --> 00:01:34,159
go through some of the

37
00:01:39,990 --> 00:01:36,960
basics of extrasolar planets quickly and

38
00:01:42,710 --> 00:01:40,000

then rapidly move to recent results that

39
00:01:44,789 --> 00:01:42,720
i think bear on astrobiology let me

40
00:01:45,590 --> 00:01:44,799
start first by saying that

41
00:01:47,350 --> 00:01:45,600
i

42
00:01:50,789 --> 00:01:47,360
hardly do any of the work myself

43
00:01:53,190 --> 00:01:50,799
nowadays i have spectacular team members

44
00:01:54,870 --> 00:01:53,200
paul butler deborah fisher steve though

45
00:01:58,069 --> 00:01:54,880
jason wright john johnson our new

46
00:02:00,230 --> 00:01:58,079
postdocs and others kdp greg henry greg

47
00:02:02,789 --> 00:02:00,240
laughlin all of whom are doing work both

48
00:02:05,429 --> 00:02:02,799
observationally and theoretically to

49
00:02:06,950 --> 00:02:05,439
help us understand the properties of

50
00:02:09,109 --> 00:02:06,960
extrasolar planets and of course the

51
00:02:11,589 --> 00:02:09,119
real message is that what's happened in

52
00:02:14,470 --> 00:02:11,599
the last 12 years is that we've gone

53
00:02:16,150 --> 00:02:14,480
from just detecting planets uh stamp

54
00:02:18,470 --> 00:02:16,160
collecting to

55
00:02:20,070 --> 00:02:18,480
characterizing the properties of planets

56
00:02:22,470 --> 00:02:20,080
and ultimately learning about their

57
00:02:26,150 --> 00:02:22,480
formation and their evolution both

58
00:02:28,309 --> 00:02:26,160
internally and dynamically so um without

59
00:02:30,630 --> 00:02:28,319
further ado let me try to bring you up

60
00:02:32,309 --> 00:02:30,640
to speed in the field of extrasolar

61
00:02:33,589 --> 00:02:32,319
planets let's see if i can actuate the

62
00:02:37,270 --> 00:02:33,599
slides here

63
00:02:41,509 --> 00:02:37,280

i can't quite yet is it gonna

64
00:02:41,519 --> 00:02:47,910
try this out

65
00:02:47,920 --> 00:02:55,509
technical difficulties

66
00:02:58,390 --> 00:02:56,470
cool

67
00:03:00,150 --> 00:02:58,400
thank you so much

68
00:03:01,990 --> 00:03:00,160
so i'll just remind you and this is a

69
00:03:04,309 --> 00:03:02,000
little bit of a shock to show a slide

70
00:03:05,030 --> 00:03:04,319
like this right away but to remind you

71
00:03:08,470 --> 00:03:05,040
that

72
00:03:11,190 --> 00:03:08,480
the vast majority of the now 250

73
00:03:13,030 --> 00:03:11,200
known extrasolar planets are detected by

74
00:03:15,270 --> 00:03:13,040
the doppler effect watching the wobble

75
00:03:17,030 --> 00:03:15,280
of the star due to the planet orbiting

76
00:03:20,470 --> 00:03:17,040
it pulling on it and you see in this

77
00:03:22,710 --> 00:03:20,480
slide overly complicated this the sketch

78
00:03:25,190 --> 00:03:22,720
the schematic of the whole technique the

79
00:03:27,670 --> 00:03:25,200
star wobbles due to the

80
00:03:29,910 --> 00:03:27,680
planet yanking on it gravitationally you

81
00:03:32,470 --> 00:03:29,920
can use the equations of energy to

82
00:03:35,350 --> 00:03:32,480
determine the velocity of the planet as

83
00:03:37,190 --> 00:03:35,360
related to the potential energy of the

84
00:03:38,550 --> 00:03:37,200
planet and then knowing the velocity of

85
00:03:40,550 --> 00:03:38,560
the planet you can use momentum

86
00:03:43,430 --> 00:03:40,560
conservation because of course the

87
00:03:45,589 --> 00:03:43,440
reflex velocity of the star will be

88
00:03:48,309 --> 00:03:45,599

reduced by the ratio of the masses the

89
00:03:50,630 --> 00:03:48,319
planet to star mass and so you expect

90
00:03:53,270 --> 00:03:50,640
from such a simple freshman level

91
00:03:55,589 --> 00:03:53,280
physics approach that stars will wobble

92
00:03:58,710 --> 00:03:55,599
with a speed of about 10 meters per

93
00:04:00,630 --> 00:03:58,720
second olympic running speed if you will

94
00:04:02,470 --> 00:04:00,640
and so that's the goal is to be able to

95
00:04:05,030 --> 00:04:02,480
measure doppler shifts

96
00:04:07,350 --> 00:04:05,040
precisely enough to detect 10 meter per

97
00:04:09,270 --> 00:04:07,360
second wobbles due to jupiter's and then

98
00:04:11,350 --> 00:04:09,280
if you want to detect neptunes and

99
00:04:13,589 --> 00:04:11,360
earths you need velocity precision

100
00:04:15,190 --> 00:04:13,599
doppler precision that's somewhat better

101
00:04:17,110 --> 00:04:15,200
and we do this of course by measuring

102
00:04:18,069 --> 00:04:17,120
the doppler effect with

103
00:04:20,229 --> 00:04:18,079
large

104
00:04:22,950 --> 00:04:20,239
world-class telescopes and similarly

105
00:04:24,950 --> 00:04:22,960
world-class spectrometers at the back of

106
00:04:26,950 --> 00:04:24,960
every one of the large telescopes that

107
00:04:29,670 --> 00:04:26,960
we use there is a spectacular

108
00:04:31,830 --> 00:04:29,680
spectrometer as shown schematically here

109
00:04:33,590 --> 00:04:31,840
and the light comes to a focus

110
00:04:36,070 --> 00:04:33,600
as after being spread out into its

111
00:04:38,150 --> 00:04:36,080
composite wavelengths at a digital

112
00:04:40,230 --> 00:04:38,160
camera ccd

113
00:04:42,310 --> 00:04:40,240

and you can see what it looks like here

114
00:04:44,629 --> 00:04:42,320
there's a typical image that we get at

115
00:04:46,070 --> 00:04:44,639
the telescope itself we use the keck

116
00:04:48,790 --> 00:04:46,080
telescope and hawaii the

117
00:04:50,310 --> 00:04:48,800
anglo-australian telescope in australia

118
00:04:52,790 --> 00:04:50,320
and of course the living rivalry

119
00:04:55,270 --> 00:04:52,800
telescope here in northern california

120
00:04:57,430 --> 00:04:55,280
and that the the challenge is actually

121
00:04:59,909 --> 00:04:57,440
daunting and has been for a decade that

122
00:05:02,150 --> 00:04:59,919
is to measure velocities of stars to a

123
00:05:04,390 --> 00:05:02,160
few meters per second which is only a

124
00:05:06,070 --> 00:05:04,400
part and ten of the nine of the speed of

125
00:05:08,710 --> 00:05:06,080
light and that means you need to be able

126
00:05:11,510 --> 00:05:08,720
to measure displacements of the spectrum

127
00:05:13,670 --> 00:05:11,520
on your ccd detector two within a few

128
00:05:15,830 --> 00:05:13,680
nanometers and you have to be able to

129
00:05:18,390 --> 00:05:15,840
come back a month later and determine

130
00:05:20,790 --> 00:05:18,400
whether the spectrum has displaced by a

131
00:05:22,629 --> 00:05:20,800
few nanometers and then a year later has

132
00:05:24,950 --> 00:05:22,639
it displaced by a few nanometers and the

133
00:05:27,270 --> 00:05:24,960
way we do this is with a trick paul

134
00:05:31,110 --> 00:05:27,280
butler and i invented this idea of

135
00:05:33,909 --> 00:05:31,120
putting iodine gas inside the telescope

136
00:05:35,590 --> 00:05:33,919
we do it with a glass cell pyrex cell

137
00:05:38,469 --> 00:05:35,600
temperature controlled the starlight

138
00:05:39,270 --> 00:05:38,479

comes in when the starlight emerges

139
00:05:39,990 --> 00:05:39,280
from

140
00:05:55,590 --> 00:05:40,000
the

141
00:05:57,990 --> 00:05:55,600
iodine lines and

142
00:05:59,990 --> 00:05:58,000
functionally we do this with a model we

143
00:06:02,310 --> 00:06:00,000
know what the iodine spectrum is we know

144
00:06:03,830 --> 00:06:02,320
what the star spectrum is and so that

145
00:06:05,590 --> 00:06:03,840
allows us to build a model of the

146
00:06:08,150 --> 00:06:05,600
observed spectrum which of course is a

147
00:06:09,990 --> 00:06:08,160
composite as shown with the dots here a

148
00:06:12,309 --> 00:06:10,000
composite of the stellar and iodine

149
00:06:14,710 --> 00:06:12,319
spectra and the model shown in the solid

150
00:06:17,590 --> 00:06:14,720
line fits very well and the one free

151
00:06:19,749 --> 00:06:17,600
parameter of course in these models is

152
00:06:22,309 --> 00:06:19,759
the doppler shift of the stellar portion

153
00:06:24,550 --> 00:06:22,319
of the spectrum so we doppler shift by

154
00:06:26,469 --> 00:06:24,560
millions of a pixel literally to get

155
00:06:30,390 --> 00:06:26,479
down to a precision of a thousandth of a

156
00:06:32,469 --> 00:06:30,400
pixel nanometer level precision as i say

157
00:06:34,550 --> 00:06:32,479
we have to use the world's largest

158
00:06:36,710 --> 00:06:34,560
telescopes because to measure such tiny

159
00:06:38,150 --> 00:06:36,720
dollar ships you need a lot of light and

160
00:06:39,830 --> 00:06:38,160
so we're using

161
00:06:41,189 --> 00:06:39,840
many of the world's largest including

162
00:06:42,390 --> 00:06:41,199
magellan

163
00:06:44,390 --> 00:06:42,400

subaru

164
00:06:45,990 --> 00:06:44,400
in addition to the three telescopes

165
00:06:48,629 --> 00:06:46,000
shown here

166
00:06:50,550 --> 00:06:48,639
just to remind you um this technique has

167
00:06:53,590 --> 00:06:50,560
of course been quite successful there's

168
00:06:55,510 --> 00:06:53,600
a team in geneva led by michelle mayor

169
00:06:56,870 --> 00:06:55,520
and he of course and their group is

170
00:06:59,029 --> 00:06:56,880
doing excellent work as well this is

171
00:07:00,950 --> 00:06:59,039
what we detect both of us we get

172
00:07:04,309 --> 00:07:00,960
velocity versus time here you see a

173
00:07:06,230 --> 00:07:04,319
decade of data and if you look carefully

174
00:07:08,309 --> 00:07:06,240
you can see the points have coherence

175
00:07:10,950 --> 00:07:08,319
the measured velocities over the course

176
00:07:14,230 --> 00:07:10,960
of time are coherent you can see the

177
00:07:17,029 --> 00:07:14,240
periodicity by i in this case about 2.2

178
00:07:19,589 --> 00:07:17,039
years by connecting the dots as you can

179
00:07:22,230 --> 00:07:19,599
do with a keplerian model and so the

180
00:07:25,029 --> 00:07:22,240
keplerian model allows you to determine

181
00:07:27,189 --> 00:07:25,039
the period but also the amplitude of the

182
00:07:29,189 --> 00:07:27,199
velocity variation which tells you the

183
00:07:31,270 --> 00:07:29,199
mass of the planet the bigger the mass

184
00:07:33,749 --> 00:07:31,280
of the planet the more strongly that

185
00:07:36,070 --> 00:07:33,759
planet must be yanking on its host star

186
00:07:37,830 --> 00:07:36,080
producing a greater reflex velocity so

187
00:07:40,150 --> 00:07:37,840
this is the basic technique we've been

188
00:07:42,150 --> 00:07:40,160

using now for for about 10 years in this

189
00:07:44,550 --> 00:07:42,160
case the mass of the planet stems

190
00:07:47,430 --> 00:07:44,560
directly from newtonian physics it's

191
00:07:49,749 --> 00:07:47,440
about 70 percent bigger than jupiter as

192
00:07:52,469 --> 00:07:49,759
you all know there's an ambiguity

193
00:07:54,869 --> 00:07:52,479
because we don't know the tilt

194
00:07:57,749 --> 00:07:54,879
plane very precisely so we don't know

195
00:07:59,909 --> 00:07:57,759
the mass of the planet absolutely but we

196
00:08:02,469 --> 00:07:59,919
get a lower limit to that mass and the

197
00:08:04,950 --> 00:08:02,479
typical mass will be some 20 or 30

198
00:08:07,270 --> 00:08:04,960
percent higher than the

199
00:08:09,029 --> 00:08:07,280
implied mass here so that's the basic

200
00:08:11,110 --> 00:08:09,039
technique and of course in addition to

201
00:08:13,909 --> 00:08:11,120
the orbit and the mass of the planet we

202
00:08:16,230 --> 00:08:13,919
also get the shape of the orbit from the

203
00:08:19,430 --> 00:08:16,240
shape of that velocity curve and in this

204
00:08:21,990 --> 00:08:19,440
case that sawtooth pattern that you saw

205
00:08:24,070 --> 00:08:22,000
implies of course an elliptical orbit

206
00:08:26,790 --> 00:08:24,080
and that's shown here schematically for

207
00:08:29,670 --> 00:08:26,800
16 cygni b you can see the elliptical

208
00:08:31,830 --> 00:08:29,680
orbit uh relative to the inner four

209
00:08:33,190 --> 00:08:31,840
planets of our solar system and so we

210
00:08:34,550 --> 00:08:33,200
actually drive a fair amount of

211
00:08:36,709 --> 00:08:34,560
information just from the doppler

212
00:08:39,269 --> 00:08:36,719
techniques rather amazing no doubt of

213
00:08:42,949 --> 00:08:39,279

light from the planet we get the planets

214
00:08:46,070 --> 00:08:42,959
semi-major axis size of the orbit the

215
00:08:48,150 --> 00:08:46,080
eccentricity of that orbital shape and

216
00:08:50,150 --> 00:08:48,160
the lower limit to the mass of the

217
00:08:52,230 --> 00:08:50,160
planet and frankly that's all we get we

218
00:08:54,470 --> 00:08:52,240
really don't get much more information

219
00:08:56,630 --> 00:08:54,480
than that but of course from the size of

220
00:08:58,710 --> 00:08:56,640
the orbit we can begin to infer the

221
00:09:01,990 --> 00:08:58,720
temperature of the planet from the

222
00:09:03,030 --> 00:09:02,000
distance between the star and the planet

223
00:09:05,990 --> 00:09:03,040
um

224
00:09:07,590 --> 00:09:06,000
sheepishly i have to show this uh

225
00:09:10,630 --> 00:09:07,600
wonderful drawing

226
00:09:12,230 --> 00:09:10,640
from lynette cook's uh

227
00:09:14,470 --> 00:09:12,240
paintbrush

228
00:09:15,509 --> 00:09:14,480
it's useful sometimes to have in your

229
00:09:17,670 --> 00:09:15,519
mind

230
00:09:19,430 --> 00:09:17,680
an artist rendering so that the

231
00:09:22,070 --> 00:09:19,440
physics that we know and what we don't

232
00:09:24,310 --> 00:09:22,080
know is sort of highlighted and here is

233
00:09:27,110 --> 00:09:24,320
this rendering of 16 cygni

234
00:09:29,750 --> 00:09:27,120
b and actually the star a as well the

235
00:09:31,030 --> 00:09:29,760
planet is in fact orbiting b

236
00:09:33,269 --> 00:09:31,040
and um

237
00:09:35,269 --> 00:09:33,279
because this planet is jupiter sized as

238
00:09:37,509 --> 00:09:35,279

is the case for many in fact the

239
00:09:39,990 --> 00:09:37,519
majority of our planets we suspect that

240
00:09:42,230 --> 00:09:40,000
the composition is gaseous it's hard to

241
00:09:44,790 --> 00:09:42,240
imagine a planet the size of jupiter

242
00:09:46,790 --> 00:09:44,800
being pure rock or rock iron and nickel

243
00:09:49,030 --> 00:09:46,800
so it's probably got plenty of volatile

244
00:09:50,630 --> 00:09:49,040
hydrogen and helium and then lynette

245
00:09:53,190 --> 00:09:50,640
cook has added something for which we

246
00:09:55,190 --> 00:09:53,200
have no evidence at all namely a moon

247
00:09:57,910 --> 00:09:55,200
and of course one exciting aspect is

248
00:10:00,389 --> 00:09:57,920
that uh the giant planets in our own

249
00:10:02,630 --> 00:10:00,399
solar system all have blooms so it's

250
00:10:04,710 --> 00:10:02,640
quite possible that many if not most of

251
00:10:07,030 --> 00:10:04,720
the giant planets we're discovering have

252
00:10:08,790 --> 00:10:07,040
moons some of them perhaps fairly large

253
00:10:10,949 --> 00:10:08,800
in this case the eccentric orbit would

254
00:10:13,990 --> 00:10:10,959
drag both the planet and the moon in so

255
00:10:16,470 --> 00:10:14,000
close that any water on the moon would

256
00:10:17,430 --> 00:10:16,480
sublimate and i think there's no chance

257
00:10:19,990 --> 00:10:17,440
for

258
00:10:22,069 --> 00:10:20,000
water on the surface at least of this of

259
00:10:23,829 --> 00:10:22,079
this sort of moon

260
00:10:26,470 --> 00:10:23,839
um let me now

261
00:10:28,150 --> 00:10:26,480
run through the types of planets we've

262
00:10:31,110 --> 00:10:28,160
detected so far

263
00:10:34,150 --> 00:10:31,120

and interestingly one type that gets

264
00:10:36,550 --> 00:10:34,160
very little attention surprisingly to me

265
00:10:39,990 --> 00:10:36,560
is the type shown here here's one of our

266
00:10:43,190 --> 00:10:40,000
stars we're surveying 2 000

267
00:10:44,949 --> 00:10:43,200
solar type stars f g k and m type stars

268
00:10:47,590 --> 00:10:44,959
and you see the velocity over the course

269
00:10:49,829 --> 00:10:47,600
of time with a nice clear

270
00:10:52,310 --> 00:10:49,839
orbital motion capillary in motion the

271
00:10:55,269 --> 00:10:52,320
period is nearly six years and the

272
00:10:57,430 --> 00:10:55,279
minimum mass about three jupiter masses

273
00:10:59,910 --> 00:10:57,440
and what's i think lovely about this

274
00:11:02,230 --> 00:10:59,920
example is of course the planet stands

275
00:11:04,389 --> 00:11:02,240
out like a sore thumb but it's also a

276
00:11:06,230 --> 00:11:04,399
fairly long orbital period something

277
00:11:08,710 --> 00:11:06,240
between the orbital periods of mars and

278
00:11:10,310 --> 00:11:08,720
jupiter and this is representative of

279
00:11:14,069 --> 00:11:10,320
many of the planets that are beginning

280
00:11:16,949 --> 00:11:14,079
to emerge now in our survey planets with

281
00:11:20,230 --> 00:11:16,959
orbital distances from their star

282
00:11:22,870 --> 00:11:20,240
nearly as large as jupiter is from our

283
00:11:24,870 --> 00:11:22,880
sun six years jupiter's orbital period

284
00:11:27,829 --> 00:11:24,880
about 12 years so we're beginning to

285
00:11:29,670 --> 00:11:27,839
find planets that remind us very much of

286
00:11:31,670 --> 00:11:29,680
our the giant planets in our solar

287
00:11:33,910 --> 00:11:31,680
system this one being more massive and

288
00:11:36,710 --> 00:11:33,920

you see right away an eccentric orbit

289
00:11:38,949 --> 00:11:36,720
the eccentricity of almost 0.5 that

290
00:11:41,190 --> 00:11:38,959
turns out to be the rule uh rather than

291
00:11:43,190 --> 00:11:41,200
the exception most of the planets we're

292
00:11:45,030 --> 00:11:43,200
finding giant planets and smaller as

293
00:11:47,590 --> 00:11:45,040
i'll discuss are in orbits that are

294
00:11:49,190 --> 00:11:47,600
eccentric not nearly circular as they

295
00:11:51,430 --> 00:11:49,200
are in our solar system

296
00:11:53,350 --> 00:11:51,440
here's another lovely example of these

297
00:11:55,430 --> 00:11:53,360
planets that get too little attention

298
00:11:57,509 --> 00:11:55,440
planets with large orbital periods

299
00:11:59,910 --> 00:11:57,519
reminding us of jupiter this is velocity

300
00:12:02,630 --> 00:11:59,920
versus time again 10 years you see a

301
00:12:04,870 --> 00:12:02,640
nice curve only in the last few months

302
00:12:06,310 --> 00:12:04,880
did we see it close we weren't sure if

303
00:12:08,389 --> 00:12:06,320
the velocities would just keep going

304
00:12:10,230 --> 00:12:08,399
down but instead

305
00:12:12,710 --> 00:12:10,240
they've turned up and that's very

306
00:12:14,389 --> 00:12:12,720
exciting to us because now you see how

307
00:12:16,629 --> 00:12:14,399
exciting it was to us with all the data

308
00:12:18,389 --> 00:12:16,639
points we have there um we're

309
00:12:20,069 --> 00:12:18,399
we now know that the orbital period is

310
00:12:22,389 --> 00:12:20,079
about nine years almost that of

311
00:12:25,430 --> 00:12:22,399
jupiter's and the mass the minimum mass

312
00:12:28,069 --> 00:12:25,440
turns out to be 1.0 jupiter masses so

313
00:12:31,670 --> 00:12:28,079

this is yet another sign that other

314
00:12:34,389 --> 00:12:31,680
stars like the sun uh quite often have

315
00:12:37,110 --> 00:12:34,399
planets that remind us closely of the

316
00:12:39,670 --> 00:12:37,120
giant planets in our own solar system

317
00:12:40,550 --> 00:12:39,680
jupiter's and saturn's are not at all

318
00:12:43,110 --> 00:12:40,560
rare

319
00:12:46,150 --> 00:12:43,120
some five or so percent i

320
00:12:48,470 --> 00:12:46,160
i estimate by some modest extrapolation

321
00:12:51,030 --> 00:12:48,480
five or ten percent of all of the

322
00:12:52,389 --> 00:12:51,040
sunlight stars have planets something

323
00:12:55,190 --> 00:12:52,399
like this one

324
00:12:57,269 --> 00:12:55,200
jupiter-sized jupiter-like orbit in this

325
00:13:00,310 --> 00:12:57,279
case the eccentricity is modest but we

326
00:13:02,150 --> 00:13:00,320
need more data points uh to be sure

327
00:13:04,310 --> 00:13:02,160
of course we're finding a lot of planets

328
00:13:06,790 --> 00:13:04,320
that are smaller and here's two

329
00:13:09,430 --> 00:13:06,800
representatives

330
00:13:11,350 --> 00:13:09,440
velocity versus orbital phase we quite

331
00:13:13,509 --> 00:13:11,360
easily pick out planets of 30 earth

332
00:13:16,389 --> 00:13:13,519
masses or so in these two examples

333
00:13:19,030 --> 00:13:16,399
albeit with very short orbital periods

334
00:13:21,670 --> 00:13:19,040
but you can see how easily planets of a

335
00:13:23,509 --> 00:13:21,680
few tens of earth masses stand out um

336
00:13:25,269 --> 00:13:23,519
and these are quite old data now where

337
00:13:27,829 --> 00:13:25,279
our velocity precision is even better

338
00:13:30,150 --> 00:13:27,839

now than it was when we took most of

339
00:13:32,550 --> 00:13:30,160
these data points so planets of of

340
00:13:34,470 --> 00:13:32,560
sub-saturn mass stand out we're also

341
00:13:37,990 --> 00:13:34,480
finding a lot of multiple planet systems

342
00:13:39,509 --> 00:13:38,000
there are now 22 well established and i

343
00:13:42,230 --> 00:13:39,519
can tell you there's three more that are

344
00:13:43,750 --> 00:13:42,240
yet to be announced multiple planet

345
00:13:46,870 --> 00:13:43,760
systems and here's one that's quite

346
00:13:49,030 --> 00:13:46,880
obvious to your eye velocity versus time

347
00:13:51,190 --> 00:13:49,040
again you're seeing eight years or so

348
00:13:54,310 --> 00:13:51,200
and you can see there's one periodicity

349
00:13:56,150 --> 00:13:54,320
superimposed on another periodicity so

350
00:13:58,389 --> 00:13:56,160
there's no question there are at least

351
00:13:59,990 --> 00:13:58,399
two planets in this system and you can

352
00:14:02,389 --> 00:14:00,000
decompose

353
00:14:04,310 --> 00:14:02,399
this velocity variation into each of the

354
00:14:06,389 --> 00:14:04,320
two planets in this case the planets

355
00:14:08,629 --> 00:14:06,399
don't interact gravitationally so you

356
00:14:11,030 --> 00:14:08,639
can simply use a model that consists of

357
00:14:12,870 --> 00:14:11,040
two planets each one orbiting their host

358
00:14:14,949 --> 00:14:12,880
star as if they were orbiting by

359
00:14:16,790 --> 00:14:14,959
themselves and so it's the sum of the

360
00:14:19,430 --> 00:14:16,800
effects of both of these two planets

361
00:14:22,310 --> 00:14:19,440
that yield the wobble of the star

362
00:14:25,110 --> 00:14:22,320
so this is a remarkable i think uh

363
00:14:28,550 --> 00:14:25,120

emerging new subfield in extrasolar

364
00:14:31,350 --> 00:14:28,560
planets the study of the origin and the

365
00:14:33,829 --> 00:14:31,360
subsequent dynamics of multiple planet

366
00:14:35,430 --> 00:14:33,839
systems and in particular the dynamics

367
00:14:36,910 --> 00:14:35,440
are highlighted by some interesting

368
00:14:40,069 --> 00:14:36,920
systems this is

369
00:14:43,509 --> 00:14:40,079
hd128311 sunlight star velocity versus

370
00:14:45,910 --> 00:14:43,519
time this very odd almost ugly looking

371
00:14:48,069 --> 00:14:45,920
velocity variation but it can be

372
00:14:51,430 --> 00:14:48,079
decomposed as in the previous case into

373
00:14:53,670 --> 00:14:51,440
two simple uh polarian orbits with

374
00:14:57,670 --> 00:14:53,680
orbital periods that are in the ratio of

375
00:15:00,550 --> 00:14:57,680
uh two to one this is 458 days 918 days

376
00:15:04,150 --> 00:15:00,560
and indeed n-body simulations show that

377
00:15:05,750 --> 00:15:04,160
this system is in a two-to-one dynamical

378
00:15:07,670 --> 00:15:05,760
mean motion resonance that is the

379
00:15:10,150 --> 00:15:07,680
planets are not just they don't just

380
00:15:12,310 --> 00:15:10,160
happen to have orbital period ratios of

381
00:15:14,790 --> 00:15:12,320
two to one but in fact they dynamically

382
00:15:17,030 --> 00:15:14,800
gravitationally shepherd each other

383
00:15:19,269 --> 00:15:17,040
maintaining that two to one ratio of

384
00:15:21,910 --> 00:15:19,279
their orbital periods uh and presumably

385
00:15:23,750 --> 00:15:21,920
will do so essentially forever so one

386
00:15:25,990 --> 00:15:23,760
question that emerges from any system

387
00:15:28,389 --> 00:15:26,000
like this is it just a fluke that the

388
00:15:31,350 --> 00:15:28,399

planets formed in these two to one

389
00:15:34,230 --> 00:15:31,360
period ratios or is there some dynamical

390
00:15:35,269 --> 00:15:34,240
uh evolution that trapped them into

391
00:15:37,509 --> 00:15:35,279
these

392
00:15:39,670 --> 00:15:37,519
resonances and i think it's the latter

393
00:15:42,150 --> 00:15:39,680
we have now three or four actually four

394
00:15:44,470 --> 00:15:42,160
i can think of mean motion resonances

395
00:15:47,030 --> 00:15:44,480
that's too many to just be a coincidence

396
00:15:47,990 --> 00:15:47,040
so i think what is now quite a dramatic

397
00:15:49,910 --> 00:15:48,000
result

398
00:15:52,310 --> 00:15:49,920
stemming from these mean motion

399
00:15:54,550 --> 00:15:52,320
resonances is the

400
00:15:56,629 --> 00:15:54,560
clear evidence that planets form

401
00:15:58,870 --> 00:15:56,639
wherever they happen to and then they

402
00:16:01,189 --> 00:15:58,880
migrate in their protoplanetary disks

403
00:16:03,350 --> 00:16:01,199
and may occasionally capture each other

404
00:16:06,389 --> 00:16:03,360
into these mean motion resonance these

405
00:16:09,509 --> 00:16:06,399
serve as a clear evidence of migration

406
00:16:12,550 --> 00:16:09,519
of the planets within the early few tens

407
00:16:15,509 --> 00:16:12,560
of millions of years of the system

408
00:16:17,990 --> 00:16:15,519
here's a very recent case we just

409
00:16:21,189 --> 00:16:18,000
announced this a couple three weeks ago

410
00:16:23,509 --> 00:16:21,199
55 concrete g8 star

411
00:16:26,389 --> 00:16:23,519
same mass as the sun a little bit less

412
00:16:27,990 --> 00:16:26,399
uh same chemical composition as the sun

413
00:16:31,030 --> 00:16:28,000

about the same age as the sun here's

414
00:16:33,110 --> 00:16:31,040
velocity versus time remarkably and i

415
00:16:35,189 --> 00:16:33,120
mean almost embarrassed to say this the

416
00:16:37,470 --> 00:16:35,199
first data points were taken in late

417
00:16:43,269 --> 00:16:37,480
1988

418
00:16:45,910 --> 00:16:43,279
and i starting way back in the dark ages

419
00:16:48,150 --> 00:16:45,920
and now you see 18 years of data points

420
00:16:50,949 --> 00:16:48,160
your eye picks out a long period

421
00:16:53,350 --> 00:16:50,959
periodicity you see all of this scatter

422
00:16:54,629 --> 00:16:53,360
and immediately a fourier power spectrum

423
00:16:57,790 --> 00:16:54,639
shows yes

424
00:16:59,430 --> 00:16:57,800
there's a 14-year period and this

425
00:17:00,470 --> 00:16:59,440
14-day

426
00:17:02,230 --> 00:17:00,480
period

427
00:17:03,910 --> 00:17:02,240
those are the two planets that emerged

428
00:17:04,789 --> 00:17:03,920
relatively quickly in the first few

429
00:17:06,949 --> 00:17:04,799
years

430
00:17:09,110 --> 00:17:06,959
if you then build a model that has those

431
00:17:11,189 --> 00:17:09,120
two planets subtract that from the

432
00:17:14,230 --> 00:17:11,199
observed data points and look at what's

433
00:17:16,549 --> 00:17:14,240
left over the velocity residuals you can

434
00:17:19,189 --> 00:17:16,559
then take a power spectrum of them and

435
00:17:21,429 --> 00:17:19,199
here's what you see a very tall delta

436
00:17:24,230 --> 00:17:21,439
function at 44 days

437
00:17:27,909 --> 00:17:24,240
that might ring a bell because 44.3 is

438
00:17:29,669 --> 00:17:27,919

exactly a factor of three more than 14.6

439
00:17:32,230 --> 00:17:29,679
so there's a suggestion of a three to

440
00:17:34,390 --> 00:17:32,240
one mean motion resonance if you then

441
00:17:36,310 --> 00:17:34,400
include that planet into your model for

442
00:17:39,029 --> 00:17:36,320
with all three planets look at the

443
00:17:42,390 --> 00:17:39,039
residuals take a power spectrum again

444
00:17:44,710 --> 00:17:42,400
now you see a 2.8 day planet emerge and

445
00:17:46,789 --> 00:17:44,720
our collaborators at texas barbara

446
00:17:47,750 --> 00:17:46,799
macarthur and bill cochran did a great

447
00:17:49,350 --> 00:17:47,760
job of

448
00:17:50,870 --> 00:17:49,360
extracting this from

449
00:17:52,710 --> 00:17:50,880
texas data

450
00:17:55,350 --> 00:17:52,720
now you have a fourth planet build a

451
00:17:57,590 --> 00:17:55,360
model with four planets subtract the

452
00:18:00,310 --> 00:17:57,600
effects of all of them and what's left

453
00:18:02,070 --> 00:18:00,320
now is yet one last planet that we've

454
00:18:04,950 --> 00:18:02,080
found this was the one we announced a

455
00:18:06,950 --> 00:18:04,960
few weeks ago 260 days there's really no

456
00:18:09,270 --> 00:18:06,960
way around this you might scratch your

457
00:18:11,590 --> 00:18:09,280
head as we have for years can you

458
00:18:14,230 --> 00:18:11,600
somehow argue that there isn't a fifth

459
00:18:15,750 --> 00:18:14,240
planet and you just can't there's no way

460
00:18:17,830 --> 00:18:15,760
around it your residuals they're going

461
00:18:20,390 --> 00:18:17,840
to have this periodicity it shows up

462
00:18:23,990 --> 00:18:20,400
both at keck and at lick independently

463
00:18:26,230 --> 00:18:24,000

so this is the first five planet system

464
00:18:27,990 --> 00:18:26,240
uh and it's got some structural

465
00:18:29,909 --> 00:18:28,000
similarities to our own solar system

466
00:18:31,750 --> 00:18:29,919
here's the fifth planet by the way yeah

467
00:18:33,830 --> 00:18:31,760
it looks ugly but then you should expect

468
00:18:35,590 --> 00:18:33,840
that getting that last planet out of the

469
00:18:37,830 --> 00:18:35,600
data extracting it from the other four

470
00:18:39,350 --> 00:18:37,840
planets isn't going to be easy and it's

471
00:18:41,510 --> 00:18:39,360
going to be the most difficult of the

472
00:18:43,510 --> 00:18:41,520
five planets to detect but there's no

473
00:18:45,909 --> 00:18:43,520
question about the periodicity just by i

474
00:18:47,510 --> 00:18:45,919
never mind fourier analysis

475
00:18:50,230 --> 00:18:47,520
and the system has similarities

476
00:18:51,990 --> 00:18:50,240
architecturally here's 55 kangri

477
00:18:53,990 --> 00:18:52,000
four inner planets

478
00:18:56,710 --> 00:18:54,000
all having lower mass than the outer

479
00:18:58,150 --> 00:18:56,720
planet of four jupiter masses and of

480
00:19:00,549 --> 00:18:58,160
course our solar system with four

481
00:19:02,630 --> 00:19:00,559
terrestrial planets and a jupiter mass

482
00:19:03,510 --> 00:19:02,640
and even the saturn mass out farther

483
00:19:06,150 --> 00:19:03,520
away

484
00:19:07,510 --> 00:19:06,160
so it's remarkable that both have this

485
00:19:11,029 --> 00:19:07,520
gap

486
00:19:13,669 --> 00:19:11,039
our solar system we don't know what's in

487
00:19:15,190 --> 00:19:13,679
the gap a 55 kangaroo we can put limits

488
00:19:17,510 --> 00:19:15,200

on what planets

489
00:19:20,310 --> 00:19:17,520
would if they were there we would have

490
00:19:22,070 --> 00:19:20,320
detected and it's about 20 earth masses

491
00:19:24,710 --> 00:19:22,080
so there's something if there's anything

492
00:19:26,870 --> 00:19:24,720
in this gap in 55 cancer it's less than

493
00:19:28,470 --> 00:19:26,880
a few tens of earth masses and of course

494
00:19:29,430 --> 00:19:28,480
i think it's very exciting to think

495
00:19:31,669 --> 00:19:29,440
about

496
00:19:33,029 --> 00:19:31,679
how we might detect whatever's in there

497
00:19:36,070 --> 00:19:33,039
debris

498
00:19:38,710 --> 00:19:36,080
maybe with infrared methods or

499
00:19:40,390 --> 00:19:38,720
planets by some other method

500
00:19:42,789 --> 00:19:40,400
and by the way the habitable zone is

501
00:19:44,789 --> 00:19:42,799
shown here in the green so the the

502
00:19:47,029 --> 00:19:44,799
fourth planet out that we just announced

503
00:19:48,950 --> 00:19:47,039
is at the inner our region of the

504
00:19:51,750 --> 00:19:48,960
habitable zone and it leaves a little

505
00:19:53,669 --> 00:19:51,760
bit of possibility of of a sixth planet

506
00:19:55,669 --> 00:19:53,679
that would be in the outskirts of the

507
00:19:57,909 --> 00:19:55,679
habitable zone here it is again one of

508
00:19:59,750 --> 00:19:57,919
the fun things of many things you can do

509
00:20:01,590 --> 00:19:59,760
with this system besides the dynamics i

510
00:20:03,590 --> 00:20:01,600
can only have time to talk about one of

511
00:20:07,029 --> 00:20:03,600
them that i enjoy you can imagine taking

512
00:20:09,590 --> 00:20:07,039
a hammer and smashing all of the planets

513
00:20:12,310 --> 00:20:09,600

in the 55 cancry system smearing out the

514
00:20:15,190 --> 00:20:12,320
material out of which they formed into a

515
00:20:17,750 --> 00:20:15,200
disc presumably the disc that the

516
00:20:19,029 --> 00:20:17,760
planets formed from and by doing that

517
00:20:20,390 --> 00:20:19,039
you can learn something about the

518
00:20:22,549 --> 00:20:20,400
density distribution of the

519
00:20:24,630 --> 00:20:22,559
protoplanetary disk out of which the

520
00:20:25,669 --> 00:20:24,640
platform and of course the surface mass

521
00:20:27,110 --> 00:20:25,679
density

522
00:20:29,110 --> 00:20:27,120
and you find that the surface mass

523
00:20:31,669 --> 00:20:29,120
density is several times higher than the

524
00:20:34,470 --> 00:20:31,679
minimum mass solar nebula and the total

525
00:20:36,789 --> 00:20:34,480
mass of the disk is almost a tenth of a

526
00:20:38,870 --> 00:20:36,799
solar mass so this is a disc that

527
00:20:41,029 --> 00:20:38,880
presumably was healthier if you will a

528
00:20:44,149 --> 00:20:41,039
little richer than the

529
00:20:46,710 --> 00:20:44,159
minimum mass solar nebula i mentioned we

530
00:20:48,630 --> 00:20:46,720
have 22 secure multi-planet systems

531
00:20:50,390 --> 00:20:48,640
here's a schematic of them the quality

532
00:20:52,310 --> 00:20:50,400
of this graph isn't very high but the

533
00:20:54,230 --> 00:20:52,320
star is shown on the left and the main

534
00:20:55,830 --> 00:20:54,240
point of this pod is to just show we're

535
00:20:58,549 --> 00:20:55,840
finding many many

536
00:21:00,549 --> 00:20:58,559
planetary systems with two three four

537
00:21:02,549 --> 00:21:00,559
now five planets clearly our

538
00:21:04,710 --> 00:21:02,559

detectability is unable to find the

539
00:21:06,870 --> 00:21:04,720
terrestrial planets so many of these

540
00:21:09,430 --> 00:21:06,880
probably have even more planets

541
00:21:12,230 --> 00:21:09,440
but what's lovely about these is that

542
00:21:14,710 --> 00:21:12,240
it's the interactions of the planets

543
00:21:16,950 --> 00:21:14,720
and their current mean motion resonances

544
00:21:20,070 --> 00:21:16,960
other types of resonances that give us

545
00:21:22,630 --> 00:21:20,080
clues especially the theorists clues

546
00:21:24,230 --> 00:21:22,640
about how the planets must have formed

547
00:21:25,909 --> 00:21:24,240
and migrated to get into the

548
00:21:28,630 --> 00:21:25,919
configurations they're in so i think

549
00:21:30,470 --> 00:21:28,640
this is a very rich area

550
00:21:33,270 --> 00:21:30,480
from the observational side to pursue

551
00:21:35,669 --> 00:21:33,280
these and then uh pursue all of the uh

552
00:21:37,990 --> 00:21:35,679
theoretical implications

553
00:21:40,549 --> 00:21:38,000
the distribution of masses of extrasolar

554
00:21:42,470 --> 00:21:40,559
planets is shown here um probably all of

555
00:21:45,909 --> 00:21:42,480
you know this result but here's the most

556
00:21:48,310 --> 00:21:45,919
recent one the 215 the best quality

557
00:21:50,310 --> 00:21:48,320
planets are shown here the rise toward

558
00:21:52,310 --> 00:21:50,320
lower and lower masses

559
00:21:54,789 --> 00:21:52,320
with a sort of a nearly power law

560
00:21:56,789 --> 00:21:54,799
dependence and what's exciting of course

561
00:21:58,950 --> 00:21:56,799
is the notion that even though these are

562
00:22:02,070 --> 00:21:58,960
this is a jupiter scale here from 0 to

563
00:22:04,789 --> 00:22:02,080

15 jupiter masses clearly below

564
00:22:06,470 --> 00:22:04,799
saturn mass the mass distribution is

565
00:22:08,950 --> 00:22:06,480
still rising and there's every reason to

566
00:22:12,149 --> 00:22:08,960
think that nature makes more neptunes

567
00:22:14,789 --> 00:22:12,159
than saturn's and as i would suggest in

568
00:22:17,510 --> 00:22:14,799
a few moments i imagine nature makes

569
00:22:19,990 --> 00:22:17,520
even more rocky planets than the

570
00:22:21,669 --> 00:22:20,000
neptunes and gas giants

571
00:22:23,510 --> 00:22:21,679
so that's an exciting

572
00:22:25,510 --> 00:22:23,520
result at this stage

573
00:22:26,630 --> 00:22:25,520
we also have the eccentricities which is

574
00:22:28,630 --> 00:22:26,640
telling us something a little

575
00:22:31,029 --> 00:22:28,640
frightening from the astrobiology

576
00:22:32,789 --> 00:22:31,039
standpoint orbital eccentricity versus

577
00:22:35,830 --> 00:22:32,799
semi-major axis

578
00:22:38,549 --> 00:22:35,840
at 1au here's the earth for reference

579
00:22:40,549 --> 00:22:38,559
1au very low eccentricity but you see

580
00:22:43,350 --> 00:22:40,559
the vast majority of the extrasolar

581
00:22:46,070 --> 00:22:43,360
planets have eccentricities much above

582
00:22:48,149 --> 00:22:46,080
the circular orbits of our solar system

583
00:22:49,830 --> 00:22:48,159
and the i don't i unfortunately don't

584
00:22:51,909 --> 00:22:49,840
have time to talk about the many

585
00:22:53,669 --> 00:22:51,919
brilliant models that have been put

586
00:22:55,430 --> 00:22:53,679
forth to explain

587
00:22:58,149 --> 00:22:55,440
the wide variety of orbital

588
00:22:59,990 --> 00:22:58,159

eccentricities

589
00:23:01,909 --> 00:23:00,000
nobody knows why they're in these

590
00:23:04,950 --> 00:23:01,919
eccentric orbits but

591
00:23:06,630 --> 00:23:04,960
the rough sketch is when planets form

592
00:23:08,950 --> 00:23:06,640
either when they're still in their sort

593
00:23:10,950 --> 00:23:08,960
of embryonic stage or later on when

594
00:23:13,190 --> 00:23:10,960
they're mature they gravitationally

595
00:23:14,950 --> 00:23:13,200
interact with each other perhaps also

596
00:23:17,190 --> 00:23:14,960
interacting with the disc out of which

597
00:23:19,750 --> 00:23:17,200
they form and that

598
00:23:21,190 --> 00:23:19,760
bumper car era the scattering of planets

599
00:23:23,669 --> 00:23:21,200
against each other

600
00:23:26,470 --> 00:23:23,679
tends to throw them out of the original

601
00:23:29,029 --> 00:23:26,480
circular orbits in which they formed

602
00:23:30,310 --> 00:23:29,039
by by various means and that leads to

603
00:23:32,950 --> 00:23:30,320
distributions like this there's some

604
00:23:35,110 --> 00:23:32,960
wonderful models that reproduce

605
00:23:36,870 --> 00:23:35,120
now this diagram the distribution of

606
00:23:39,909 --> 00:23:36,880
eccentricities of course you notice the

607
00:23:41,990 --> 00:23:39,919
closest in planets are mostly have very

608
00:23:44,310 --> 00:23:42,000
circular orbits due to tidal

609
00:23:47,110 --> 00:23:44,320
circularization tidal effects with the

610
00:23:51,029 --> 00:23:48,870
so this is an exciting result and i

611
00:23:54,870 --> 00:23:51,039
think what's worthy of some note from an

612
00:23:56,870 --> 00:23:54,880
astrobiology standpoint is this last

613
00:23:59,350 --> 00:23:56,880

corner of domain

614
00:24:01,830 --> 00:23:59,360
in here the orbital

615
00:24:04,230 --> 00:24:01,840
semi-major axes are two and a half aus

616
00:24:07,029 --> 00:24:04,240
and beyond notice the scatter and

617
00:24:09,750 --> 00:24:07,039
eccentricities these are giant planets

618
00:24:12,470 --> 00:24:09,760
akin to our own jupiter at five a use

619
00:24:14,470 --> 00:24:12,480
5.2 ages and there's no evidence that

620
00:24:17,110 --> 00:24:14,480
these planets have any more circular

621
00:24:19,350 --> 00:24:17,120
orbits than do all the other planets so

622
00:24:21,750 --> 00:24:19,360
the suggestion is that giant planets

623
00:24:23,830 --> 00:24:21,760
even out at 5 a.u.s

624
00:24:26,390 --> 00:24:23,840
tend to have eccentricities

625
00:24:28,230 --> 00:24:26,400
that span a wide range and are much

626
00:24:30,470 --> 00:24:28,240
greater than the eccentricities of the

627
00:24:32,549 --> 00:24:30,480
of the planets in our own solar system

628
00:24:34,870 --> 00:24:32,559
will be lovely of course to get a few

629
00:24:37,990 --> 00:24:34,880
more planets out here five to ten aus

630
00:24:40,870 --> 00:24:38,000
and see if any of them tend more toward

631
00:24:42,950 --> 00:24:40,880
circular orbits statistically

632
00:24:45,029 --> 00:24:42,960
the semi-major axis distribution of the

633
00:24:46,470 --> 00:24:45,039
planets is shown here i think the one

634
00:24:48,630 --> 00:24:46,480
take-home message from this you're

635
00:24:51,029 --> 00:24:48,640
seeing semi-major access and the number

636
00:24:53,830 --> 00:24:51,039
of them the take-home message and people

637
00:24:56,310 --> 00:24:53,840
somehow haven't uh this hasn't made the

638
00:24:58,950 --> 00:24:56,320

the newspapers or or the consciousness

639
00:25:01,750 --> 00:24:58,960
of even scientists in large part that

640
00:25:04,789 --> 00:25:01,760
most of the extrasolar planets known

641
00:25:06,630 --> 00:25:04,799
orbit beyond 1au somehow people think

642
00:25:08,390 --> 00:25:06,640
that many or most of the extrasolar

643
00:25:10,470 --> 00:25:08,400
planets are very close in the hot

644
00:25:12,070 --> 00:25:10,480
jupiters are making the headlines but in

645
00:25:15,269 --> 00:25:12,080
fact the majority of known extrasolar

646
00:25:17,110 --> 00:25:15,279
planets orbit farther out than than 1au

647
00:25:20,310 --> 00:25:17,120
and and there's certainly

648
00:25:22,950 --> 00:25:20,320
a selection effect against finding these

649
00:25:25,110 --> 00:25:22,960
planets out at 5 and 10 au's because

650
00:25:26,870 --> 00:25:25,120
their orbital periods are so long that

651
00:25:29,430 --> 00:25:26,880
we haven't had a chance to detect them

652
00:25:31,590 --> 00:25:29,440
also the wobble of the star is lower so

653
00:25:33,590 --> 00:25:31,600
between the poor detectability and this

654
00:25:35,590 --> 00:25:33,600
large hump that you're seeing here it

655
00:25:37,430 --> 00:25:35,600
almost looks and i wonder if this is

656
00:25:39,750 --> 00:25:37,440
beginning to become true that there's

657
00:25:41,830 --> 00:25:39,760
sort of a discontinuity here maybe

658
00:25:44,310 --> 00:25:41,840
associated with the ice line that is

659
00:25:47,110 --> 00:25:44,320
often talked about such that giant

660
00:25:49,269 --> 00:25:47,120
planets form uh quite efficiently beyond

661
00:25:51,430 --> 00:25:49,279
an au but not so efficiently inward or

662
00:25:53,830 --> 00:25:51,440
maybe there's a migration issue that the

663
00:25:56,149 --> 00:25:53,840

planets migrate inward and

664
00:25:58,549 --> 00:25:56,159
slip in very quickly leaving a paucity

665
00:26:00,630 --> 00:25:58,559
of giant planets in here so this is an

666
00:26:03,430 --> 00:26:00,640
exciting new area where we're beginning

667
00:26:05,750 --> 00:26:03,440
to see the giant planets emerge and

668
00:26:07,990 --> 00:26:05,760
determine what their prevalence is and

669
00:26:09,990 --> 00:26:08,000
again i with some extrapolation you can

670
00:26:12,470 --> 00:26:10,000
say that some 13

671
00:26:15,110 --> 00:26:12,480
of all stars that we are surveying 2 000

672
00:26:17,830 --> 00:26:15,120
nearby stars some 13 of them seem to

673
00:26:19,510 --> 00:26:17,840
have giant planets kin of our own giant

674
00:26:21,430 --> 00:26:19,520
planets in our solar system by the way

675
00:26:24,310 --> 00:26:21,440
some 85 or 7

676
00:26:26,149 --> 00:26:24,320
of the stars don't have giant planets at

677
00:26:28,230 --> 00:26:26,159
least jupiter sized

678
00:26:29,909 --> 00:26:28,240
i think this is the most important plot

679
00:26:31,669 --> 00:26:29,919
of my whole talk

680
00:26:33,190 --> 00:26:31,679
it comes from work by deborah fisher and

681
00:26:35,190 --> 00:26:33,200
jeff valencia

682
00:26:36,950 --> 00:26:35,200
and it's now well known but it's worth

683
00:26:38,710 --> 00:26:36,960
reiterating this effect is not going

684
00:26:39,830 --> 00:26:38,720
away and its interpretation is being

685
00:26:42,630 --> 00:26:39,840
clarified

686
00:26:45,430 --> 00:26:42,640
the probability that a planet sorry the

687
00:26:48,070 --> 00:26:45,440
probability that a star has a planet

688
00:26:49,990 --> 00:26:48,080

is directly related to the uh

689
00:26:51,590 --> 00:26:50,000
metallicity of the abundance of the

690
00:26:53,430 --> 00:26:51,600
heavy elements within

691
00:26:55,029 --> 00:26:53,440
the stars the host stars and we

692
00:26:56,789 --> 00:26:55,039
characterize that in a strong in

693
00:27:00,630 --> 00:26:56,799
astrophysics with the iron to hydrogen

694
00:27:03,269 --> 00:27:00,640
ratio it's a log scale the sun is 0.00

695
00:27:05,510 --> 00:27:03,279
but you see that stars that have more

696
00:27:08,070 --> 00:27:05,520
heavy elements have a higher probability

697
00:27:10,789 --> 00:27:08,080
of harboring planets very dramatic

698
00:27:13,669 --> 00:27:10,799
effect incontrovertible and the most

699
00:27:15,430 --> 00:27:13,679
likely interpretation is the simplest

700
00:27:18,310 --> 00:27:15,440
one actually and the one you would have

701
00:27:20,710 --> 00:27:18,320
thought of namely protoplanetary disks

702
00:27:22,470 --> 00:27:20,720
that are rich in heavy elements oxygen

703
00:27:25,029 --> 00:27:22,480
silicon iron nickel

704
00:27:27,190 --> 00:27:25,039
have a lot more dust per unit mass than

705
00:27:29,510 --> 00:27:27,200
they otherwise would have and that extra

706
00:27:30,549 --> 00:27:29,520
dust mass allows planet growth to be

707
00:27:35,669 --> 00:27:30,559
enhanced

708
00:27:38,390 --> 00:27:35,679
giants more quickly before the gas is

709
00:27:41,269 --> 00:27:38,400
dissipated away and models now confirm

710
00:27:43,510 --> 00:27:41,279
that this trend can be reproduced with

711
00:27:46,230 --> 00:27:43,520
theory and i list some of the authors of

712
00:27:48,149 --> 00:27:46,240
the models again lynn and hornet and ed

713
00:27:50,310 --> 00:27:48,159

thomas and others so there's very

714
00:27:51,830 --> 00:27:50,320
exciting result here that suggests and i

715
00:27:54,310 --> 00:27:51,840
want to mention what i think is an

716
00:27:57,350 --> 00:27:54,320
extrapolation of the interpretation

717
00:28:00,310 --> 00:27:57,360
heavy elements leads to planets and most

718
00:28:03,269 --> 00:28:00,320
specifically leads to coagulation of

719
00:28:05,909 --> 00:28:03,279
dust giving you the rocky cords that are

720
00:28:08,149 --> 00:28:05,919
the obviously the necessities of both

721
00:28:10,789 --> 00:28:08,159
giant planets but obviously also the

722
00:28:12,310 --> 00:28:10,799
terrestrial planets this plot alone

723
00:28:13,029 --> 00:28:12,320
suggests to me

724
00:28:15,430 --> 00:28:13,039
that

725
00:28:17,350 --> 00:28:15,440
dust growth leads to terrestrial planets

726
00:28:19,110 --> 00:28:17,360
they must be numerous even though we

727
00:28:21,269 --> 00:28:19,120
haven't detected any earth-like

728
00:28:23,110 --> 00:28:21,279
earth-sized planets yet

729
00:28:26,149 --> 00:28:23,120
this conclusion about

730
00:28:29,029 --> 00:28:26,159
rocky cores being the building blocks

731
00:28:32,710 --> 00:28:29,039
for planets in general is shown by two

732
00:28:34,789 --> 00:28:32,720
spectacular cases hd149026

733
00:28:38,149 --> 00:28:34,799
velocity versus orbital phase you see

734
00:28:40,710 --> 00:28:38,159
the keplerian motion it's only a 2.9 day

735
00:28:43,590 --> 00:28:40,720
orbital period deborah fischer and

736
00:28:45,669 --> 00:28:43,600
brunei sato greg laflin discovered this

737
00:28:48,310 --> 00:28:45,679
it was then quickly found that the

738
00:28:50,630 --> 00:28:48,320

planet transits the star dimming the

739
00:28:52,310 --> 00:28:50,640
star repeatedly over and over again

740
00:28:54,789 --> 00:28:52,320
worked by greg henry

741
00:28:56,310 --> 00:28:54,799
that dimming tells you the radius of the

742
00:28:59,590 --> 00:28:56,320
planet the bigger the planet the more

743
00:29:01,669 --> 00:28:59,600
light is blocked and so schematically uh

744
00:29:03,350 --> 00:29:01,679
you can see the situation here planet

745
00:29:06,710 --> 00:29:03,360
transiting blocking the starlight giving

746
00:29:08,870 --> 00:29:06,720
us its radius and then hence the density

747
00:29:11,269 --> 00:29:08,880
of the planet and what's amazing about

748
00:29:13,269 --> 00:29:11,279
this planet is that its density is even

749
00:29:16,630 --> 00:29:13,279
higher than that of saturn's even though

750
00:29:18,630 --> 00:29:16,640
its mass is about the same as saturn's

751
00:29:20,710 --> 00:29:18,640
how can you make a planet that has about

752
00:29:23,269 --> 00:29:20,720
the same mass of saturn but a much

753
00:29:25,430 --> 00:29:23,279
higher density it must be that there's

754
00:29:27,110 --> 00:29:25,440
more heavy elements within the planet

755
00:29:29,909 --> 00:29:27,120
either in a core or distributed

756
00:29:32,230 --> 00:29:29,919
throughout and in any case it means that

757
00:29:35,269 --> 00:29:32,240
saturn's rocky core of 20 earth masses

758
00:29:37,990 --> 00:29:35,279
or so that's known um must be and if

759
00:29:40,350 --> 00:29:38,000
there must be an even larger rocky core

760
00:29:42,230 --> 00:29:40,360
inside this planet of

761
00:29:44,070 --> 00:29:42,240
hd-149026 and you see peter

762
00:29:45,070 --> 00:29:44,080
bodenheimer's model here

763
00:29:48,549 --> 00:29:45,080

the planet

764
00:29:50,549 --> 00:29:48,559
149026b with this enhanced core required

765
00:29:52,070 --> 00:29:50,559
to explain the radius

766
00:29:55,110 --> 00:29:52,080
that we see

767
00:29:57,029 --> 00:29:55,120
a second example of this uh prevalence

768
00:30:00,389 --> 00:29:57,039
of rocky cores is shown in this one

769
00:30:03,590 --> 00:30:00,399
gliese 436 this is an m dwarf a third of

770
00:30:04,710 --> 00:30:03,600
a solar mass you see our keck velocities

771
00:30:05,669 --> 00:30:04,720
here again

772
00:30:09,190 --> 00:30:05,679
um

773
00:30:12,549 --> 00:30:09,200
in incontrovertibly planet 22.6 earth

774
00:30:15,669 --> 00:30:12,559
masses 2.6 day very close in planet

775
00:30:17,510 --> 00:30:15,679
luckily here again it transited um

776
00:30:19,269 --> 00:30:17,520
and i'll show you in the next slide but

777
00:30:21,269 --> 00:30:19,279
the eccentricity is interesting too

778
00:30:25,750 --> 00:30:21,279
here's the the beautiful i think

779
00:30:27,510 --> 00:30:25,760
spectacular work by gion at all 2007

780
00:30:30,230 --> 00:30:27,520
showing the dimming of the star we've

781
00:30:32,070 --> 00:30:30,240
seen now hundreds of these transits of

782
00:30:35,269 --> 00:30:32,080
the planet across the surface of the

783
00:30:37,510 --> 00:30:35,279
star uh giving us the radius and the new

784
00:30:39,110 --> 00:30:37,520
estimate of the radius uh you may if

785
00:30:40,950 --> 00:30:39,120
you've been following this here's a new

786
00:30:45,110 --> 00:30:40,960
radius that's a little bigger than the

787
00:30:46,230 --> 00:30:45,120
original radius that jion got 4.3 earth

788
00:30:47,990 --> 00:30:46,240

radii

789
00:30:50,070 --> 00:30:48,000
coupled with the mass from the doppler

790
00:30:52,870 --> 00:30:50,080
effect gives us the density and the

791
00:30:55,110 --> 00:30:52,880
density is remarkable 1.6 grams per

792
00:30:57,590 --> 00:30:55,120
cubic centimeter that again is much

793
00:31:01,269 --> 00:30:57,600
higher than saturn's density

794
00:31:02,789 --> 00:31:01,279
and again suggests a large rocky core

795
00:31:03,669 --> 00:31:02,799
here is the model

796
00:31:05,669 --> 00:31:03,679
that

797
00:31:07,990 --> 00:31:05,679
in fact jonathan fortney and mark marley

798
00:31:11,110 --> 00:31:08,000
and others put together here at nasa

799
00:31:13,510 --> 00:31:11,120
ames and um it's

800
00:31:15,590 --> 00:31:13,520
this story is not over that you can see

801
00:31:16,870 --> 00:31:15,600
from the model that they put forth a

802
00:31:18,950 --> 00:31:16,880
rocky core

803
00:31:21,269 --> 00:31:18,960
something like the rocky

804
00:31:24,470 --> 00:31:21,279
interior of neptune

805
00:31:25,909 --> 00:31:24,480
a very thick water envelope and then

806
00:31:28,870 --> 00:31:25,919
probably

807
00:31:31,190 --> 00:31:28,880
and indeed lightly a fairly thick

808
00:31:33,110 --> 00:31:31,200
hydrogen helium shell

809
00:31:37,029 --> 00:31:33,120
now the problem is

810
00:31:38,230 --> 00:31:37,039
that the relative amounts of rock water

811
00:31:41,590 --> 00:31:38,240
and gas

812
00:31:43,430 --> 00:31:41,600
can't really be unambiguously determined

813
00:31:45,029 --> 00:31:43,440

the degeneracy of course is due to the

814
00:31:47,269 --> 00:31:45,039
fact that all three components have a

815
00:31:47,990 --> 00:31:47,279
very different density and therefore you

816
00:31:50,470 --> 00:31:48,000
can

817
00:31:52,950 --> 00:31:50,480
mix together various amounts of two out

818
00:31:56,389 --> 00:31:52,960
of the three and reproduce the observed

819
00:31:58,549 --> 00:31:56,399
density it's about 1.55 grams per cc so

820
00:32:01,269 --> 00:31:58,559
we can't really say for sure that this

821
00:32:03,590 --> 00:32:01,279
planet definitely has a rocky core and

822
00:32:06,149 --> 00:32:03,600
this much water or this much hydrogen

823
00:32:09,029 --> 00:32:06,159
and helium it must have admixtures that

824
00:32:10,950 --> 00:32:09,039
give you this final density probably if

825
00:32:12,070 --> 00:32:10,960
you fold in our knowledge of planet

826
00:32:14,710 --> 00:32:12,080
formation

827
00:32:16,630 --> 00:32:14,720
this density uh what we know about the

828
00:32:19,509 --> 00:32:16,640
location of the planet and how it got

829
00:32:21,750 --> 00:32:19,519
there probably this model i would say is

830
00:32:23,750 --> 00:32:21,760
about right if i had to bed if someone

831
00:32:26,470 --> 00:32:23,760
forced you to bed you'd bet yeah there's

832
00:32:28,710 --> 00:32:26,480
a big rocky core water

833
00:32:31,350 --> 00:32:28,720
envelope and then a hydrogen helium

834
00:32:33,750 --> 00:32:31,360
shell okay can i interrupt sure sorry

835
00:32:36,710 --> 00:32:33,760
andrew yeah but you keep saying rocky

836
00:32:39,029 --> 00:32:36,720
right i presume you're including metal

837
00:32:41,110 --> 00:32:39,039
are you talking about something

838
00:32:43,430 --> 00:32:41,120

absolutely and i was going to say light

839
00:32:46,470 --> 00:32:43,440
the earth or like terrestrial planets

840
00:32:49,029 --> 00:32:46,480
probably an iron nickel central part of

841
00:32:51,269 --> 00:32:49,039
the core and then a silicate outer

842
00:32:52,470 --> 00:32:51,279
portion all of which makes up the core

843
00:32:54,070 --> 00:32:52,480
absolutely

844
00:32:57,029 --> 00:32:54,080
yeah

845
00:33:00,310 --> 00:32:57,039
so this is what's exciting here in part

846
00:33:01,190 --> 00:33:00,320
is the ambiguity clearly what we need

847
00:33:05,350 --> 00:33:01,200
now

848
00:33:07,590 --> 00:33:05,360
are planets that transit like lisa 436

849
00:33:09,430 --> 00:33:07,600
but which are smaller maybe 10 earth

850
00:33:11,909 --> 00:33:09,440
masses or five earth masses for which we

851
00:33:13,590 --> 00:33:11,919
can play the same game get the density

852
00:33:16,630 --> 00:33:13,600
and it would be just great if we could

853
00:33:19,029 --> 00:33:16,640
get a population of observed planets of

854
00:33:21,029 --> 00:33:19,039
a few earth masses for which we get

855
00:33:22,950 --> 00:33:21,039
their densities and determine whether

856
00:33:24,470 --> 00:33:22,960
they are indeed rocky in which case

857
00:33:26,789 --> 00:33:24,480
their densities of course would be that

858
00:33:29,029 --> 00:33:26,799
of roughly the earth or venus by five

859
00:33:31,830 --> 00:33:29,039
and a half grams per cc so that's an

860
00:33:35,509 --> 00:33:31,840
exciting future uh goal

861
00:33:37,590 --> 00:33:35,519
gliese 876 i think remains i in my view

862
00:33:39,750 --> 00:33:37,600
the most spectacular of the discoveries

863
00:33:42,870 --> 00:33:39,760

so far here's the data from rivera and

864
00:33:45,590 --> 00:33:42,880
lissauer at all you see velocity versus

865
00:33:47,830 --> 00:33:45,600
time for over a decade best fit with a

866
00:33:50,149 --> 00:33:47,840
three planet model what's amazing is the

867
00:33:52,389 --> 00:33:50,159
outer two jupiters are in a two to one

868
00:33:54,870 --> 00:33:52,399
mean motion resonance the fit is very

869
00:33:57,110 --> 00:33:54,880
good only if you add the third planet

870
00:33:59,430 --> 00:33:57,120
and that's shown here it's an inner

871
00:34:01,990 --> 00:33:59,440
planet with a period of two days and you

872
00:34:03,830 --> 00:34:02,000
see the minimum mass is only 5.9 earth

873
00:34:05,909 --> 00:34:03,840
masses i will tell you somewhat

874
00:34:08,950 --> 00:34:05,919
cryptically that in my opinion this is

875
00:34:10,069 --> 00:34:08,960
still the best case of a very low mass

876
00:34:12,310 --> 00:34:10,079
planet

877
00:34:15,109 --> 00:34:12,320
that exists out there and when you throw

878
00:34:16,869 --> 00:34:15,119
in the our knowledge of the tilt of the

879
00:34:18,869 --> 00:34:16,879
orbital plane that we get from the outer

880
00:34:20,869 --> 00:34:18,879
two planets in their dynamics the mass

881
00:34:23,109 --> 00:34:20,879
comes out to be seven and a half her

882
00:34:25,430 --> 00:34:23,119
masses so this is again a suggestion

883
00:34:27,510 --> 00:34:25,440
that nature does indeed make planets of

884
00:34:29,829 --> 00:34:27,520
lower and lower mass in greater and

885
00:34:31,510 --> 00:34:29,839
greater numbers uh this being one of the

886
00:34:34,470 --> 00:34:31,520
few stars for which we could have

887
00:34:35,750 --> 00:34:34,480
detected a few earth mass planet and we

888
00:34:37,349 --> 00:34:35,760

did

889
00:34:39,430 --> 00:34:37,359
so it's quite exciting of course this

890
00:34:41,669 --> 00:34:39,440
one is too hot with an orbital period of

891
00:34:43,349 --> 00:34:41,679
two days to have liquid water uh

892
00:34:45,829 --> 00:34:43,359
anywhere on its surface oh and i should

893
00:34:47,829 --> 00:34:45,839
add by going back a slide we really

894
00:34:49,349 --> 00:34:47,839
don't know the composition of this

895
00:34:52,149 --> 00:34:49,359
planet it doesn't transit we don't have

896
00:34:54,710 --> 00:34:52,159
its density so whether it's rocky or has

897
00:34:56,310 --> 00:34:54,720
a large complement of water ice like

898
00:34:59,030 --> 00:34:56,320
neptune we don't know

899
00:35:02,790 --> 00:34:59,040
if i had to bet i'm stretching here my

900
00:35:05,270 --> 00:35:02,800
guess is planets of 5 to 10 earth masses

901
00:35:07,990 --> 00:35:05,280
suggestion is they are more akin to

902
00:35:11,589 --> 00:35:08,000
neptune than our earth i bet planets of

903
00:35:14,950 --> 00:35:11,599
that size attract isis and have a big

904
00:35:20,230 --> 00:35:18,230
um quickly here's an exciting uh new

905
00:35:23,190 --> 00:35:20,240
kind of planet that i'm not sure all of

906
00:35:25,589 --> 00:35:23,200
you are aware of it's it's so much fun

907
00:35:29,510 --> 00:35:25,599
uh there's a an astronomer who's a

908
00:35:31,510 --> 00:35:29,520
postdoc at harvard um gaspar bakosh who

909
00:35:33,670 --> 00:35:31,520
is finding transiting planets in large

910
00:35:35,030 --> 00:35:33,680
numbers here you see the dimming of the

911
00:35:37,270 --> 00:35:35,040
star

912
00:35:40,310 --> 00:35:37,280
due to the planet crossing in front and

913
00:35:42,470 --> 00:35:40,320

the analysis by bhagosh and joshuin is

914
00:35:45,109 --> 00:35:42,480
shown in the next few slides here are

915
00:35:47,670 --> 00:35:45,119
our velocities taken at keck for the

916
00:35:50,950 --> 00:35:47,680
wobble of the star yes the star wobbles

917
00:35:51,829 --> 00:35:50,960
it's an eccentric orbit of 0.5 that's

918
00:35:53,910 --> 00:35:51,839
fine

919
00:35:56,150 --> 00:35:53,920
the planet transits its star but what's

920
00:35:58,630 --> 00:35:56,160
interesting is that here the keplerian

921
00:36:00,790 --> 00:35:58,640
behavior is kind of off somehow and if

922
00:36:02,630 --> 00:36:00,800
you zoom in on that little domain you

923
00:36:05,270 --> 00:36:02,640
see that the velocities due to the

924
00:36:08,230 --> 00:36:05,280
keplerian are disturbed in this sort of

925
00:36:12,069 --> 00:36:08,240
s shape and the reason it's disturbed is

926
00:36:15,030 --> 00:36:12,079
that as the planet crosses the star it

927
00:36:17,109 --> 00:36:15,040
first blocks the approaching edge or

928
00:36:20,470 --> 00:36:17,119
limb of the star and then the planet

929
00:36:22,470 --> 00:36:20,480
blocks the receding edge of the star and

930
00:36:23,990 --> 00:36:22,480
so there's a net doppler shift due to

931
00:36:25,670 --> 00:36:24,000
the fact that the approaching light is

932
00:36:27,270 --> 00:36:25,680
flat and then the receding light is

933
00:36:29,990 --> 00:36:27,280
blocked so you're actually getting a

934
00:36:33,510 --> 00:36:30,000
sense of the direction of motion of the

935
00:36:35,990 --> 00:36:33,520
planet relative to the spin of the star

936
00:36:39,270 --> 00:36:36,000
and if you do the math so to speak you

937
00:36:41,190 --> 00:36:39,280
can easily confirm that these data with

938
00:36:43,910 --> 00:36:41,200

the velocity going high and that

939
00:36:45,990 --> 00:36:43,920
redshift and then low tells you that the

940
00:36:48,950 --> 00:36:46,000
angular momentum of the orbit of the

941
00:36:52,710 --> 00:36:48,960
planet is in the same direction vectorly

942
00:36:54,870 --> 00:36:52,720
as the spin angular momentum of the star

943
00:36:56,630 --> 00:36:54,880
just as it is in our own solar system

944
00:36:59,190 --> 00:36:56,640
and there are about five other cases

945
00:37:01,349 --> 00:36:59,200
that joshua has been following that show

946
00:37:02,870 --> 00:37:01,359
exactly the same thing so perhaps you

947
00:37:04,790 --> 00:37:02,880
would have predicted this but it turns

948
00:37:06,870 --> 00:37:04,800
out all of the planets for which we've

949
00:37:09,190 --> 00:37:06,880
done this kind of analysis

950
00:37:11,829 --> 00:37:09,200
show that the orbits and the spin of the

951
00:37:14,230 --> 00:37:11,839
star are in the same direction

952
00:37:16,870 --> 00:37:14,240
um here is a blow-up of joshua's

953
00:37:19,750 --> 00:37:16,880
beautiful modeling showing the uh the

954
00:37:22,310 --> 00:37:19,760
velocity wobble due to this this uh this

955
00:37:24,230 --> 00:37:22,320
effect it's quite exciting and of course

956
00:37:26,150 --> 00:37:24,240
we would love to find a case that didn't

957
00:37:27,510 --> 00:37:26,160
obey this if you could find a case where

958
00:37:29,430 --> 00:37:27,520
the star was spinning one way of the

959
00:37:31,430 --> 00:37:29,440
planet going the other way that would

960
00:37:33,109 --> 00:37:31,440
raise some eyebrows

961
00:37:34,630 --> 00:37:33,119
so it's quite an exciting new field

962
00:37:37,030 --> 00:37:34,640
where we're learning something about the

963
00:37:39,510 --> 00:37:37,040

dynamics of migration

964
00:37:42,630 --> 00:37:39,520
now i'd like to spend the last six or

965
00:37:44,790 --> 00:37:42,640
seven minutes of my talk in

966
00:37:47,109 --> 00:37:44,800
a little bit of a frightening

967
00:37:49,030 --> 00:37:47,119
area so i want to caution you ahead of

968
00:37:50,710 --> 00:37:49,040
time that what i'm about to say

969
00:37:53,510 --> 00:37:50,720
for the most part i don't know what i'm

970
00:37:55,829 --> 00:37:53,520
talking about and uh so you can take

971
00:37:58,390 --> 00:37:55,839
what i say with a grain of salt but i

972
00:38:01,670 --> 00:37:58,400
wanted i looked back at the past

973
00:38:03,589 --> 00:38:01,680
um director's seminar series talks

974
00:38:05,750 --> 00:38:03,599
that carl pilcher and his team have put

975
00:38:07,030 --> 00:38:05,760
on the web and i was surprised that no

976
00:38:09,589 --> 00:38:07,040
one

977
00:38:12,150 --> 00:38:09,599
that i could see reached out and

978
00:38:14,230 --> 00:38:12,160
speculated about intelligent life

979
00:38:15,910 --> 00:38:14,240
advanced life in the galaxy so i

980
00:38:18,550 --> 00:38:15,920
couldn't help but give my two cents

981
00:38:20,550 --> 00:38:18,560
worth albeit uninformed and of course

982
00:38:22,470 --> 00:38:20,560
the calculation that frank drake would

983
00:38:24,790 --> 00:38:22,480
do right away is to say well our galaxy

984
00:38:26,710 --> 00:38:24,800
has 200 billion stars we now have

985
00:38:28,870 --> 00:38:26,720
detected 10

986
00:38:31,030 --> 00:38:28,880
uh of them having planets of course we

987
00:38:31,829 --> 00:38:31,040
can only find the

988
00:38:34,069 --> 00:38:31,839

neptunes jupiter's

989
00:38:36,150 --> 00:38:34,079
saturns but the suggestion would be that

990
00:38:38,390 --> 00:38:36,160
there are something like 20 billion

991
00:38:40,870 --> 00:38:38,400
planetary systems that have these giant

992
00:38:43,030 --> 00:38:40,880
planets alone never mind all of the

993
00:38:45,430 --> 00:38:43,040
systems that may have smaller planets

994
00:38:47,190 --> 00:38:45,440
that we can't yet detect of earth size

995
00:38:49,430 --> 00:38:47,200
but there's every suggestion for planet

996
00:38:51,510 --> 00:38:49,440
formation theory that to the extent that

997
00:38:53,750 --> 00:38:51,520
jupiter's and saturn's are common the

998
00:38:56,069 --> 00:38:53,760
smaller rocky planets will be even more

999
00:38:58,630 --> 00:38:56,079
common and the models suggest this

1000
00:39:01,910 --> 00:38:58,640
clearly so there are at least some 20

1001
00:39:04,390 --> 00:39:01,920
billion planetary systems within our

1002
00:39:06,550 --> 00:39:04,400
milky way and then of course those of

1003
00:39:08,950 --> 00:39:06,560
you who saw norm pace's talk i was

1004
00:39:11,190 --> 00:39:08,960
enjoying watching it on the web of the

1005
00:39:13,990 --> 00:39:11,200
director's seminar series

1006
00:39:16,150 --> 00:39:14,000
norm started his talk i saw with this

1007
00:39:18,790 --> 00:39:16,160
quote so i wanted to remind you what

1008
00:39:20,870 --> 00:39:18,800
norm said terrestrial life has

1009
00:39:22,230 --> 00:39:20,880
penetrated all permissible thermodynamic

1010
00:39:23,910 --> 00:39:22,240
and physical niches offered by the

1011
00:39:25,349 --> 00:39:23,920
planet earth all of us know that

1012
00:39:27,589 --> 00:39:25,359
consequently it is likely that

1013
00:39:30,069 --> 00:39:27,599

terrestrial life offers models for life

1014
00:39:31,510 --> 00:39:30,079
in almost any habitable niche in the

1015
00:39:33,430 --> 00:39:31,520
universe of course that's sort of an

1016
00:39:36,470 --> 00:39:33,440
underlying

1017
00:39:38,550 --> 00:39:36,480
tenet of the nasa astrobiology institute

1018
00:39:40,710 --> 00:39:38,560
but it's remarkable that even from the

1019
00:39:43,910 --> 00:39:40,720
molecular biology standpoint from the

1020
00:39:46,230 --> 00:39:43,920
tree of life standpoint uh those of you

1021
00:39:48,069 --> 00:39:46,240
who are studying this come to this sort

1022
00:39:50,790 --> 00:39:48,079
of a conclusion stemming from the

1023
00:39:52,230 --> 00:39:50,800
extremophiles that show us that in you

1024
00:39:54,870 --> 00:39:52,240
know

1025
00:39:57,270 --> 00:39:54,880
environments that seem hideous life

1026
00:39:59,750 --> 00:39:57,280
thrives anyway and that of course offers

1027
00:40:01,589 --> 00:39:59,760
us a suggestion in the extrasolar planet

1028
00:40:03,270 --> 00:40:01,599
business

1029
00:40:05,670 --> 00:40:03,280
and now here's where the speculation

1030
00:40:08,790 --> 00:40:05,680
really goes wild now if you go back to

1031
00:40:10,069 --> 00:40:08,800
the 20 billion planetary systems many of

1032
00:40:11,349 --> 00:40:10,079
them of course are going to be older

1033
00:40:13,430 --> 00:40:11,359
than the earth

1034
00:40:15,190 --> 00:40:13,440
frank drake and carl sagan and so many

1035
00:40:18,550 --> 00:40:15,200
other people ask well what fraction of

1036
00:40:20,230 --> 00:40:18,560
them might spawn complex multicellular

1037
00:40:23,829 --> 00:40:20,240
life for which darwinian evolution would

1038
00:40:25,510 --> 00:40:23,839

have a chance of proceeding toward uh

1039
00:40:27,109 --> 00:40:25,520
and of course

1040
00:40:28,870 --> 00:40:27,119
we don't know i mean i think the most

1041
00:40:31,109 --> 00:40:28,880
remarkable

1042
00:40:33,589 --> 00:40:31,119
portion of ignorance about biology in my

1043
00:40:35,589 --> 00:40:33,599
mind is we can't tell the evolutionary

1044
00:40:37,990 --> 00:40:35,599
biologist cannot tell us

1045
00:40:40,950 --> 00:40:38,000
what fraction of the time single celled

1046
00:40:42,790 --> 00:40:40,960
life on a nice docile tranquil

1047
00:40:44,630 --> 00:40:42,800
habitable planet will lead to

1048
00:40:46,870 --> 00:40:44,640
intelligent life so

1049
00:40:48,310 --> 00:40:46,880
as we all know in frank drake's world

1050
00:40:50,710 --> 00:40:48,320
you pick a number

1051
00:40:53,030 --> 00:40:50,720
one in a million can be multiplied by 20

1052
00:40:55,750 --> 00:40:53,040
billion and you find out as the science

1053
00:40:57,589 --> 00:40:55,760
fiction writers have known forever that

1054
00:40:59,510 --> 00:40:57,599
there should be thousands of advanced

1055
00:41:02,550 --> 00:40:59,520
civilizations this is the standard

1056
00:41:04,950 --> 00:41:02,560
calculation we teach in freshman

1057
00:41:07,030 --> 00:41:04,960
astronomy classes and it still holds

1058
00:41:09,750 --> 00:41:07,040
true except i think what doesn't get

1059
00:41:11,829 --> 00:41:09,760
discussed adequately is that if there

1060
00:41:13,910 --> 00:41:11,839
are thousands of advanced civilizations

1061
00:41:15,829 --> 00:41:13,920
in our milky way galaxy the fermi

1062
00:41:17,190 --> 00:41:15,839
paradox is still

1063
00:41:19,430 --> 00:41:17,200

alive and well

1064
00:41:22,069 --> 00:41:19,440
it is still a mystery whether or not we

1065
00:41:24,230 --> 00:41:22,079
want to admit it that with all of the

1066
00:41:25,910 --> 00:41:24,240
ways we could have detected advanced

1067
00:41:29,510 --> 00:41:25,920
life that could have sent robotic

1068
00:41:31,430 --> 00:41:29,520
spacecraft to the moon set up cameras

1069
00:41:33,349 --> 00:41:31,440
same with mars they could have set up

1070
00:41:35,670 --> 00:41:33,359
golf courses here on the earth and

1071
00:41:37,589 --> 00:41:35,680
vacation resorts for billions of years

1072
00:41:39,829 --> 00:41:37,599
the earth was a shangri-la they didn't

1073
00:41:42,309 --> 00:41:39,839
do that there are footprints of course

1074
00:41:44,150 --> 00:41:42,319
on the moon but they're ours so it's

1075
00:41:46,069 --> 00:41:44,160
remarkable that there's simply no

1076
00:41:48,309 --> 00:41:46,079
evidence that in the millions and

1077
00:41:50,950 --> 00:41:48,319
billions of years that advanced species

1078
00:41:52,470 --> 00:41:50,960
could have sent even machines here

1079
00:41:55,109 --> 00:41:52,480
there's no evidence of it and of course

1080
00:41:57,990 --> 00:41:55,119
a wide variety of other non-detections

1081
00:41:59,990 --> 00:41:58,000
of advanced life no gamma-ray uh

1082
00:42:02,710 --> 00:42:00,000
emission from the matter anti-matter

1083
00:42:04,790 --> 00:42:02,720
engines of the klingons uh you know and

1084
00:42:06,870 --> 00:42:04,800
no robotic probes orbiting our solar

1085
00:42:09,030 --> 00:42:06,880
system that we've detected seti still

1086
00:42:12,630 --> 00:42:09,040
struggling to get its first

1087
00:42:15,190 --> 00:42:12,640
detection so there is a possibility that

1088
00:42:17,349 --> 00:42:15,200

the evolutionary biologists have their

1089
00:42:19,430 --> 00:42:17,359
work cut out for them to tell us

1090
00:42:21,750 --> 00:42:19,440
why it might be that primitive life

1091
00:42:24,230 --> 00:42:21,760
should be common as norm pace's talk

1092
00:42:26,790 --> 00:42:24,240
indicated but advanced life and indeed

1093
00:42:29,430 --> 00:42:26,800
technological life at this stage could

1094
00:42:31,910 --> 00:42:29,440
be rare it could be that it's one in a

1095
00:42:34,309 --> 00:42:31,920
billion not one in a million so this

1096
00:42:37,270 --> 00:42:34,319
this fermi paradox is certainly in my

1097
00:42:38,710 --> 00:42:37,280
view um something to be considered uh

1098
00:42:41,510 --> 00:42:38,720
and it's a part of what makes nasa

1099
00:42:43,109 --> 00:42:41,520
astrobiology a real science we don't

1100
00:42:44,710 --> 00:42:43,119
know the answer it's not that we're

1101
00:42:46,950 --> 00:42:44,720
trying to look for advanced life and

1102
00:42:49,589 --> 00:42:46,960
understand it it might be that advanced

1103
00:42:50,950 --> 00:42:49,599
life isn't as common as we thought the

1104
00:42:52,550 --> 00:42:50,960
answer is known and i think that's

1105
00:42:54,630 --> 00:42:52,560
beautiful that's what science should be

1106
00:42:55,829 --> 00:42:54,640
all about not necessarily knowing the

1107
00:42:57,430 --> 00:42:55,839
answer

1108
00:43:01,430 --> 00:42:57,440
there are of course three missions

1109
00:43:04,630 --> 00:43:01,440
designed uh right now by nasa to detect

1110
00:43:07,109 --> 00:43:04,640
earth-like planets kepler is the most

1111
00:43:09,270 --> 00:43:07,119
promising launch due in a year and a

1112
00:43:11,270 --> 00:43:09,280
half of course i think everybody knows

1113
00:43:12,950 --> 00:43:11,280

kepler will detect earth-like planets by

1114
00:43:15,270 --> 00:43:12,960
the earth's crossing in front of the

1115
00:43:16,870 --> 00:43:15,280
star dimming the star

1116
00:43:18,710 --> 00:43:16,880
it's very exciting over a hundred

1117
00:43:21,430 --> 00:43:18,720
thousand stars will be monitored in

1118
00:43:23,270 --> 00:43:21,440
cygnus and lyra hoping to detect the

1119
00:43:25,829 --> 00:43:23,280
earth's but more importantly detect the

1120
00:43:28,069 --> 00:43:25,839
occurrence rate of earth's what fraction

1121
00:43:29,030 --> 00:43:28,079
of sunlight stars have rocky planets

1122
00:43:31,349 --> 00:43:29,040
like the earth and what's the

1123
00:43:33,670 --> 00:43:31,359
distribution of orbital parameters two

1124
00:43:36,230 --> 00:43:33,680
other missions sim and the terrestrial

1125
00:43:38,950 --> 00:43:36,240
planet finder are also extremely

1126
00:43:40,790 --> 00:43:38,960
promising sim frankly more than ever is

1127
00:43:42,630 --> 00:43:40,800
promising the technology is completely

1128
00:43:44,550 --> 00:43:42,640
ready to go the terrestrial planet

1129
00:43:46,630 --> 00:43:44,560
finder is less ready to go

1130
00:43:49,510 --> 00:43:46,640
architecturally but both have very

1131
00:43:51,750 --> 00:43:49,520
valuable niches especially tpf to get

1132
00:43:53,670 --> 00:43:51,760
spectra of earths and as you know budget

1133
00:43:56,550 --> 00:43:53,680
constraints have delayed these two

1134
00:43:59,349 --> 00:43:56,560
missions they will happen uh lest we all

1135
00:44:01,190 --> 00:43:59,359
be depressed and i am but there's no

1136
00:44:03,190 --> 00:44:01,200
doubt that at some point in the next few

1137
00:44:05,829 --> 00:44:03,200
decades both of these missions have to

1138
00:44:07,829 --> 00:44:05,839

happen you must get masses of earth-like

1139
00:44:10,390 --> 00:44:07,839
planets and you must get their spectra

1140
00:44:13,190 --> 00:44:10,400
to understand earth-like planets so

1141
00:44:15,190 --> 00:44:13,200
while these missions are are struggling

1142
00:44:16,630 --> 00:44:15,200
nasa's on the right track

1143
00:44:18,069 --> 00:44:16,640
in the meantime we're going to try to

1144
00:44:20,309 --> 00:44:18,079
detect earth-like planets from the

1145
00:44:22,150 --> 00:44:20,319
ground uh we're building a new telescope

1146
00:44:24,309 --> 00:44:22,160
at lick observatory that you see here

1147
00:44:26,230 --> 00:44:24,319
the dome is in the telescope is finished

1148
00:44:27,670 --> 00:44:26,240
here's the dome with san jose in the

1149
00:44:30,230 --> 00:44:27,680
background and there's a line of sight

1150
00:44:32,710 --> 00:44:30,240
to nasa ames it's right about there so

1151
00:44:34,630 --> 00:44:32,720
actually you can see the hanger

1152
00:44:37,910 --> 00:44:34,640
from lick observatory and we expect to

1153
00:44:39,670 --> 00:44:37,920
put in a microwave link very soon and

1154
00:44:41,589 --> 00:44:39,680
what's exciting about this new telescope

1155
00:44:43,510 --> 00:44:41,599
is we'll use it every single night to

1156
00:44:46,069 --> 00:44:43,520
detect earth-like planets

1157
00:44:49,510 --> 00:44:46,079
by detecting the doppler shift every

1158
00:44:52,470 --> 00:44:49,520
night you can trace out very small

1159
00:44:55,030 --> 00:44:52,480
amplitude variations here's a synthesis

1160
00:44:57,670 --> 00:44:55,040
of a 10 earth mass planet orbiting in a

1161
00:45:00,230 --> 00:44:57,680
50-day orbital period and you can see of

1162
00:45:03,430 --> 00:45:00,240
course by eye the wobble of the star

1163
00:45:05,510 --> 00:45:03,440

velocity versus time due to what mere 10

1164
00:45:07,910 --> 00:45:05,520
earth mass planet they stand out like a

1165
00:45:10,630 --> 00:45:07,920
sore thumb primarily because you have

1166
00:45:13,030 --> 00:45:10,640
such good sampling nightly sampling

1167
00:45:15,589 --> 00:45:13,040
which clearly isn't required the fourier

1168
00:45:18,630 --> 00:45:15,599
analysis shows the peak clearly what

1169
00:45:20,950 --> 00:45:18,640
about smaller mass planets two earth

1170
00:45:23,030 --> 00:45:20,960
masses again they show up here's

1171
00:45:25,430 --> 00:45:23,040
velocity versus time simulated with our

1172
00:45:28,470 --> 00:45:25,440
one and a half uh one one meter per

1173
00:45:30,390 --> 00:45:28,480
second errors you can't see the velocity

1174
00:45:33,190 --> 00:45:30,400
periodicity here but the fourier

1175
00:45:34,870 --> 00:45:33,200
analysis shows the peak very clearly

1176
00:45:37,430 --> 00:45:34,880
there so we will have no trouble

1177
00:45:40,550 --> 00:45:37,440
detecting planets of a few earth masses

1178
00:45:42,309 --> 00:45:40,560
in orbital periods of uh months that

1179
00:45:43,829 --> 00:45:42,319
reside in the habitable zone the

1180
00:45:45,589 --> 00:45:43,839
temperature by the way the equilibrium

1181
00:45:48,309 --> 00:45:45,599
temperature of this planet without

1182
00:45:49,829 --> 00:45:48,319
greenhouse effect is some adc so there

1183
00:45:52,069 --> 00:45:49,839
will be earth mass planets around

1184
00:45:53,910 --> 00:45:52,079
sunlight stars a few earth masses that

1185
00:45:56,710 --> 00:45:53,920
will stand out easily even one earth

1186
00:45:58,870 --> 00:45:56,720
mass shows up you might need two summers

1187
00:46:00,550 --> 00:45:58,880
of this telescope rather than just one

1188
00:46:02,309 --> 00:46:00,560

summary here's about one summer's worth

1189
00:46:04,790 --> 00:46:02,319
of data so it's pretty exciting that

1190
00:46:06,790 --> 00:46:04,800
from the ground even along with kepler

1191
00:46:10,309 --> 00:46:06,800
we should be able to get a handle on the

1192
00:46:12,950 --> 00:46:10,319
occurrence rate of rocky planets

1193
00:46:15,030 --> 00:46:12,960
and then finally what we really all

1194
00:46:17,190 --> 00:46:15,040
should remember is that if you find

1195
00:46:19,030 --> 00:46:17,200
inner flight planet the real uh

1196
00:46:20,870 --> 00:46:19,040
excitement will begin when you turn your

1197
00:46:22,950 --> 00:46:20,880
radio telescopes toward them and try to

1198
00:46:25,670 --> 00:46:22,960
pick up any signals and of course at the

1199
00:46:27,990 --> 00:46:25,680
seti institute with berkeley uh the paul

1200
00:46:30,470 --> 00:46:28,000
allen telescope array is being built uh

1201
00:46:32,870 --> 00:46:30,480
north of mount lassen with hundreds of

1202
00:46:35,270 --> 00:46:32,880
dishes the goal would be of course once

1203
00:46:37,750 --> 00:46:35,280
you find an earth-like planet you stare

1204
00:46:39,349 --> 00:46:37,760
at that darn thing for weeks maybe

1205
00:46:42,150 --> 00:46:39,359
months because if you know there's an

1206
00:46:43,990 --> 00:46:42,160
earth-like planet there you you put your

1207
00:46:46,390 --> 00:46:44,000
eggs in that basket

1208
00:46:48,390 --> 00:46:46,400
and try to pick up any weak signals from

1209
00:46:49,510 --> 00:46:48,400
civilizations that uh that are actually

1210
00:46:52,069 --> 00:46:49,520
transmitted

1211
00:46:54,069 --> 00:46:52,079
so i think that's the excitement um the

1212
00:46:55,390 --> 00:46:54,079
bottom line really from

1213
00:46:58,309 --> 00:46:55,400

from the

1214
00:47:00,630 --> 00:46:58,319
microbiologists among you the norm paste

1215
00:47:02,630 --> 00:47:00,640
type perspective is that the ingredients

1216
00:47:03,910 --> 00:47:02,640
for life are out there the petri dishes

1217
00:47:06,309 --> 00:47:03,920
are there the

1218
00:47:08,470 --> 00:47:06,319
stuff of life is out there the energy

1219
00:47:10,790 --> 00:47:08,480
and the water is abundant in the

1220
00:47:12,550 --> 00:47:10,800
universe in a variety of different ways

1221
00:47:15,589 --> 00:47:12,560
so i don't think any of us at least in

1222
00:47:17,910 --> 00:47:15,599
my view doubt that replicating molecules

1223
00:47:20,710 --> 00:47:17,920
of some sort will begin uh forming

1224
00:47:22,470 --> 00:47:20,720
competing and evolving the real question

1225
00:47:23,349 --> 00:47:22,480
now is whether or not there's advanced

1226
00:47:26,309 --> 00:47:23,359
life

1227
00:47:27,990 --> 00:47:26,319
anywhere in the in the galaxy

1228
00:47:30,150 --> 00:47:28,000
and i think i'll just summarize by

1229
00:47:32,230 --> 00:47:30,160
saying the real take-home message of my

1230
00:47:34,069 --> 00:47:32,240
talk i think is that

1231
00:47:36,550 --> 00:47:34,079
the fact that planet occurrence

1232
00:47:39,349 --> 00:47:36,560
correlates with metallicity of the star

1233
00:47:42,150 --> 00:47:39,359
the fact that we see the rocky cores in

1234
00:47:44,870 --> 00:47:42,160
the planets the two cases i showed tells

1235
00:47:48,150 --> 00:47:44,880
you that dust accumulation into rocky

1236
00:47:50,069 --> 00:47:48,160
bodies is a common process rocky planets

1237
00:47:52,870 --> 00:47:50,079
must be common even though we haven't

1238
00:47:55,270 --> 00:47:52,880

detected any pure rocky planets yet it

1239
00:47:57,349 --> 00:47:55,280
would be a real stretch to suggest that

1240
00:47:59,670 --> 00:47:57,359
rocky planets are rare in contrast i

1241
00:48:01,750 --> 00:47:59,680
would say rocky planets of earth size

1242
00:48:03,510 --> 00:48:01,760
are probably even more common than the

1243
00:48:06,870 --> 00:48:03,520
jupiters and the saturns there are

1244
00:48:09,270 --> 00:48:06,880
billions of earth-sized planets probably

1245
00:48:11,349 --> 00:48:09,280
within our milky way galaxy and then

1246
00:48:13,990 --> 00:48:11,359
from the kind of perspective that norm

1247
00:48:16,390 --> 00:48:14,000
uh presented primitive life probably is

1248
00:48:18,470 --> 00:48:16,400
common and the real question i think for

1249
00:48:20,390 --> 00:48:18,480
all of us is whether or not evolutionary

1250
00:48:21,750 --> 00:48:20,400
biology can tell us something

1251
00:48:24,470 --> 00:48:21,760
about the

1252
00:48:36,150 --> 00:48:24,480
occurrence of the of intelligence and

1253
00:48:41,589 --> 00:48:38,950
thank you well we now have opportunities

1254
00:48:43,510 --> 00:48:41,599
uh for people here in the room the names

1255
00:48:45,270 --> 00:48:43,520
and people around the net to ask jeff

1256
00:48:47,109 --> 00:48:45,280
questions so let me first ask if there's

1257
00:48:48,790 --> 00:48:47,119
a question here at ames and would

1258
00:48:51,109 --> 00:48:48,800
anybody around the net please raise your

1259
00:48:53,430 --> 00:48:51,119
hand on webex and we'll call on you and

1260
00:48:55,109 --> 00:48:53,440
we'll start with president nate demerit

1261
00:48:56,710 --> 00:48:55,119
yeah my question uh

1262
00:48:58,230 --> 00:48:56,720
is that this relationship between the

1263
00:48:59,030 --> 00:48:58,240

metallicity of the star which you could

1264
00:49:00,549 --> 00:48:59,040
see

1265
00:49:02,230 --> 00:49:00,559
and of course the composition of the

1266
00:49:03,829 --> 00:49:02,240
disk and i guess there's two aspects of

1267
00:49:05,670 --> 00:49:03,839
it do you think we could look at

1268
00:49:07,109 --> 00:49:05,680
metallicities of the stars to get a

1269
00:49:09,030 --> 00:49:07,119
sense of what the distribution of

1270
00:49:10,309 --> 00:49:09,040
compositions would be for the disc you

1271
00:49:11,910 --> 00:49:10,319
know with outcomes for how much

1272
00:49:13,670 --> 00:49:11,920
volatiles you might get on rocket

1273
00:49:15,910 --> 00:49:13,680
planets and so forth and then the other

1274
00:49:17,670 --> 00:49:15,920
aspect of that question is the strongly

1275
00:49:20,069 --> 00:49:17,680
migrated systems that you see where

1276
00:49:21,750 --> 00:49:20,079
jupiter's in close could they be systems

1277
00:49:23,349 --> 00:49:21,760
where a lot of stuff was dumped into the

1278
00:49:25,349 --> 00:49:23,359
star and could you see a correlation

1279
00:49:27,589 --> 00:49:25,359
between the metallicity of the star and

1280
00:49:29,589 --> 00:49:27,599
how strongly migrated the system was

1281
00:49:31,349 --> 00:49:29,599
yeah let me you've asked a number of

1282
00:49:34,150 --> 00:49:31,359
questions let me address the last one

1283
00:49:37,109 --> 00:49:34,160
first there was a controversy

1284
00:49:38,790 --> 00:49:37,119
beginning six seven years ago

1285
00:49:40,950 --> 00:49:38,800
as to whether or not the

1286
00:49:43,030 --> 00:49:40,960
correlation between them the currents of

1287
00:49:45,990 --> 00:49:43,040
planets and the metallicity of the post

1288
00:49:48,549 --> 00:49:46,000

stars was for nature or nurture is it

1289
00:49:50,950 --> 00:49:48,559
that the stars are polluted by the

1290
00:49:52,710 --> 00:49:50,960
planets themselves that dump inward and

1291
00:49:55,270 --> 00:49:52,720
there's very strong evidence now that

1292
00:49:58,390 --> 00:49:55,280
it's not the pollution and the evidence

1293
00:50:01,910 --> 00:49:58,400
in brief is that some stars have very

1294
00:50:04,470 --> 00:50:01,920
thin convective envelopes so thin that

1295
00:50:06,870 --> 00:50:04,480
any metals dumped onto the star would

1296
00:50:09,510 --> 00:50:06,880
have been trapped in that convection

1297
00:50:11,270 --> 00:50:09,520
zone unable to diffuse inward we should

1298
00:50:13,670 --> 00:50:11,280
see very dramatically enhanced

1299
00:50:16,150 --> 00:50:13,680
metallicities of those stars and we

1300
00:50:18,309 --> 00:50:16,160
don't so it's not pollution primarily

1301
00:50:20,150 --> 00:50:18,319
there might be some aspect to it right

1302
00:50:21,510 --> 00:50:20,160
it's it's a primordial effect where

1303
00:50:24,390 --> 00:50:21,520
which is what you might have guessed at

1304
00:50:26,390 --> 00:50:24,400
first glance more metals means more dust

1305
00:50:28,950 --> 00:50:26,400
and has all the planet formation models

1306
00:50:30,790 --> 00:50:28,960
have it the enhanced dust gives you more

1307
00:50:32,630 --> 00:50:30,800
planet formation

1308
00:50:34,309 --> 00:50:32,640
with regard to your other question we

1309
00:50:37,349 --> 00:50:34,319
certainly know that

1310
00:50:39,270 --> 00:50:37,359
stars in the disk of our galaxy

1311
00:50:41,430 --> 00:50:39,280
have a range of

1312
00:50:42,390 --> 00:50:41,440
metal abundances silicon oxygen iron

1313
00:50:44,710 --> 00:50:42,400

nickel

1314
00:50:46,870 --> 00:50:44,720
about a factor of two or three

1315
00:50:48,549 --> 00:50:46,880
above that of the sun and below that of

1316
00:50:50,549 --> 00:50:48,559
the sun and almost certainly the

1317
00:50:52,069 --> 00:50:50,559
protoplanetary disks

1318
00:50:54,630 --> 00:50:52,079
shared

1319
00:50:56,549 --> 00:50:54,640
that range that distribution of

1320
00:50:58,790 --> 00:50:56,559
metallicities and of course water is

1321
00:51:00,950 --> 00:50:58,800
very abundant in the protoplanetary

1322
00:51:03,349 --> 00:51:00,960
disks as a common molecule that forms on

1323
00:51:06,470 --> 00:51:03,359
the hydrogen and oxygen so my strong

1324
00:51:09,670 --> 00:51:06,480
suspicion is that planets form with

1325
00:51:12,390 --> 00:51:09,680
rocky cores quite commonly get a good

1326
00:51:14,790 --> 00:51:12,400
complement of volatiles both the ices

1327
00:51:16,950 --> 00:51:14,800
methane water ices and then hydrogen and

1328
00:51:18,710 --> 00:51:16,960
helium i think actually

1329
00:51:21,349 --> 00:51:18,720
there's still a bit of a touchy question

1330
00:51:23,829 --> 00:51:21,359
as to how you form a pure rocky planet

1331
00:51:25,349 --> 00:51:23,839
without it gobbling up some more of the

1332
00:51:27,910 --> 00:51:25,359
volatiles why does the earth have as

1333
00:51:30,549 --> 00:51:27,920
little water as it has i'm not sure

1334
00:51:33,030 --> 00:51:30,559
anyone knows the answer to that

1335
00:51:34,950 --> 00:51:33,040
um we have a question from university of

1336
00:51:36,390 --> 00:51:34,960
washington okay let's go to university

1337
00:51:38,309 --> 00:51:36,400
of washington we'll come back here to

1338
00:51:40,230 --> 00:51:38,319

ames

1339
00:51:43,190 --> 00:51:40,240
hi jeff tom quinn

1340
00:51:45,349 --> 00:51:43,200
uh could you remind me uh what the

1341
00:51:49,109 --> 00:51:45,359
eccentricity distribution of the planets

1342
00:51:50,630 --> 00:51:49,119
in 55 cancry are and would you

1343
00:51:51,589 --> 00:51:50,640
compare that with that of the solar

1344
00:51:54,549 --> 00:51:51,599
system

1345
00:51:57,349 --> 00:51:54,559
yeah thank you um they're all circular

1346
00:51:59,910 --> 00:51:57,359
um they're circular within errors um

1347
00:52:01,670 --> 00:51:59,920
the innermost planet has an eccentricity

1348
00:52:03,670 --> 00:52:01,680
of that's the highest if that's been

1349
00:52:05,910 --> 00:52:03,680
that's the 10 earth mass one right in

1350
00:52:09,349 --> 00:52:05,920
close it seems to be an existing about

1351
00:52:10,630 --> 00:52:09,359
0.15 the others are all less than 0.1

1352
00:52:12,710 --> 00:52:10,640
and in fact

1353
00:52:15,270 --> 00:52:12,720
we didn't know that until a few weeks

1354
00:52:17,510 --> 00:52:15,280
above until we published this paper

1355
00:52:19,510 --> 00:52:17,520
with only a model of four planets you

1356
00:52:22,069 --> 00:52:19,520
you are required to pump up their

1357
00:52:24,150 --> 00:52:22,079
eccentricities to explain the data but

1358
00:52:25,910 --> 00:52:24,160
now that the fifth planet is is clearly

1359
00:52:28,470 --> 00:52:25,920
there all of their eccentricity is

1360
00:52:31,829 --> 00:52:28,480
naturally dropped just you know by best

1361
00:52:33,990 --> 00:52:31,839
the best fit to uh sub attempt uh

1362
00:52:35,910 --> 00:52:34,000
eccentricity so it's a it's a system as

1363
00:52:38,790 --> 00:52:35,920

shown in the diagram with nearly

1364
00:52:41,589 --> 00:52:38,800
circular orbits

1365
00:52:42,630 --> 00:52:41,599
hey question from jeff cuzzy here

1366
00:52:44,870 --> 00:52:42,640
jeff uh

1367
00:52:45,910 --> 00:52:44,880
has any i'm sure you have uh

1368
00:52:47,510 --> 00:52:45,920
what do you get when you try to

1369
00:52:49,349 --> 00:52:47,520
correlate the eccentricity of the

1370
00:52:51,190 --> 00:52:49,359
planets with the mentalism

1371
00:52:52,710 --> 00:52:51,200
yeah the question is how about the

1372
00:52:53,910 --> 00:52:52,720
correlation between eccentricity and

1373
00:52:55,910 --> 00:52:53,920
metallicity

1374
00:52:58,309 --> 00:52:55,920
there is a little correlation it hasn't

1375
00:53:01,990 --> 00:52:58,319
gotten much air time

1376
00:53:05,109 --> 00:53:02,000
the sense is planets with large orbital

1377
00:53:06,870 --> 00:53:05,119
eccentricities and large mass above a

1378
00:53:09,510 --> 00:53:06,880
jupiter mass

1379
00:53:14,230 --> 00:53:09,520
tend to come tend to orbit stars of

1380
00:53:17,190 --> 00:53:14,240
slightly lower than average metallicity

1381
00:53:20,069 --> 00:53:17,200
as if there's a formation mechanism for

1382
00:53:21,030 --> 00:53:20,079
the massive eccentric planets

1383
00:53:23,109 --> 00:53:21,040
that

1384
00:53:25,030 --> 00:53:23,119
somehow isn't quite the same as the

1385
00:53:27,589 --> 00:53:25,040
formation mechanism of all the rest of

1386
00:53:29,990 --> 00:53:27,599
the planets maybe for example

1387
00:53:31,910 --> 00:53:30,000
gravitational instabilities plays more

1388
00:53:34,069 --> 00:53:31,920

of a role for planets of five or ten

1389
00:53:36,549 --> 00:53:34,079
jupiter masses uh than it does for

1390
00:53:37,990 --> 00:53:36,559
planets less than a jupiter mass it's a

1391
00:53:40,390 --> 00:53:38,000
it's a slight

1392
00:53:42,309 --> 00:53:40,400
tendency but we've done como graph smart

1393
00:53:44,710 --> 00:53:42,319
off tests and indeed the massive

1394
00:53:47,910 --> 00:53:44,720
eccentric planets orbit low metallicity

1395
00:53:50,870 --> 00:53:47,920
stars system attitude

1396
00:53:53,510 --> 00:53:50,880
question in the back here yeah um

1397
00:54:00,549 --> 00:53:53,520
are you using the

1398
00:54:04,069 --> 00:54:02,390
i i don't know the answer to that

1399
00:54:06,630 --> 00:54:04,079
question um

1400
00:54:09,750 --> 00:54:06,640
as you say the abundances in the sun are

1401
00:54:12,069 --> 00:54:09,760
being revised as we speak but primarily

1402
00:54:13,990 --> 00:54:12,079
the diagnostic here is iron and the

1403
00:54:16,630 --> 00:54:14,000
abundance of iron in the sun to my

1404
00:54:17,990 --> 00:54:16,640
knowledge hasn't been adjusted much

1405
00:54:20,390 --> 00:54:18,000
recently

1406
00:54:21,589 --> 00:54:20,400
right mainly

1407
00:54:24,549 --> 00:54:21,599
yes

1408
00:54:26,309 --> 00:54:24,559
and silicon neon right and and we don't

1409
00:54:28,069 --> 00:54:26,319
know as much about the abundances of

1410
00:54:29,829 --> 00:54:28,079
those elements they're harder to measure

1411
00:54:32,470 --> 00:54:29,839
and you're right there there's a state

1412
00:54:35,190 --> 00:54:32,480
of flux about their normalization iron

1413
00:54:37,430 --> 00:54:35,200

we use as a proxy and frankly a rather

1414
00:54:39,829 --> 00:54:37,440
poor proxy of the abundances of the

1415
00:54:42,710 --> 00:54:39,839
other heavy elements but so with regard

1416
00:54:44,150 --> 00:54:42,720
to the correlations i've mentioned iron

1417
00:54:47,190 --> 00:54:44,160
is really what i meant when i say

1418
00:54:51,190 --> 00:54:49,190
david morrison

1419
00:54:52,630 --> 00:54:51,200
i'd like to try to pin you down a little

1420
00:54:55,349 --> 00:54:52,640
bit on the

1421
00:54:57,750 --> 00:54:55,359
super earth up to say 10 earth masses

1422
00:54:59,349 --> 00:54:57,760
yeah very interesting for kepler because

1423
00:55:01,750 --> 00:54:59,359
that's one of the areas we'll support

1424
00:55:04,549 --> 00:55:01,760
very interesting for astrobiology sounds

1425
00:55:07,750 --> 00:55:04,559
like you're getting the first data but

1426
00:55:09,910 --> 00:55:07,760
is there actually enough data to tell if

1427
00:55:13,990 --> 00:55:09,920
there is going to be a common class of

1428
00:55:14,950 --> 00:55:14,000
planets between terrestrial and giant

1429
00:55:15,829 --> 00:55:14,960
yeah

1430
00:55:23,910 --> 00:55:15,839
the

1431
00:55:26,309 --> 00:55:23,920
between one earth mass and 14 earth

1432
00:55:27,750 --> 00:55:26,319
masses where uranus is there being a gap

1433
00:55:30,710 --> 00:55:27,760
in our own solar system in the mass

1434
00:55:32,950 --> 00:55:30,720
distribution and um we've

1435
00:55:35,190 --> 00:55:32,960
we in the swiss team now have some 10 of

1436
00:55:38,230 --> 00:55:35,200
these i think one or two of them might

1437
00:55:39,910 --> 00:55:38,240
be suspect but most of them are not um

1438
00:55:41,910 --> 00:55:39,920

and so there's clearly a class of

1439
00:55:42,870 --> 00:55:41,920
planets between one and fourteen earth

1440
00:55:45,829 --> 00:55:42,880
masses

1441
00:55:48,549 --> 00:55:45,839
probably rocky cores and some amount of

1442
00:55:49,829 --> 00:55:48,559
volatiles especially the isis so i think

1443
00:55:51,349 --> 00:55:49,839
there's no doubt that there is that

1444
00:55:53,349 --> 00:55:51,359
intermediate class of planets that

1445
00:55:54,630 --> 00:55:53,359
simply is not represented in our solar

1446
00:55:56,390 --> 00:55:54,640
system on the other hand you might think

1447
00:55:59,109 --> 00:55:56,400
of them as mini neptunes which makes

1448
00:56:03,510 --> 00:55:59,119
them continuous

1449
00:56:07,349 --> 00:56:06,549
yeah hi jeff it's mike mumma hi jeff

1450
00:56:09,990 --> 00:56:07,359
hi

1451
00:56:13,270 --> 00:56:10,000
uh jeff can you uh tell us the current

1452
00:56:16,870 --> 00:56:13,280
status of long-term dynamical modeling

1453
00:56:19,109 --> 00:56:16,880
for the planetary evolution and systems

1454
00:56:22,230 --> 00:56:19,119
that you've been uh studying for example

1455
00:56:26,309 --> 00:56:22,240
55 can cree is anybody working on that

1456
00:56:30,870 --> 00:56:28,950
it's so hot off the press it's out there

1457
00:56:34,069 --> 00:56:30,880
now of course that we put the pre-print

1458
00:56:36,549 --> 00:56:34,079
uh out three weeks ago and i have very

1459
00:56:38,150 --> 00:56:36,559
little doubt that probably in your room

1460
00:56:41,030 --> 00:56:38,160
and some of the other rooms here maybe

1461
00:56:42,710 --> 00:56:41,040
this room there are people who can do

1462
00:56:46,630 --> 00:56:42,720
the analysis either analytically or

1463
00:56:48,150 --> 00:56:46,640

numerically and i hope are busy doing so

1464
00:56:49,270 --> 00:56:48,160
there are people i know like jack

1465
00:56:50,950 --> 00:56:49,280
lissauer

1466
00:56:53,829 --> 00:56:50,960
eric ford

1467
00:56:56,470 --> 00:56:53,839
manhoy lee others who you know chomping

1468
00:56:58,789 --> 00:56:56,480
at the bit to analyze these systems i

1469
00:57:00,870 --> 00:56:58,799
strongly suspect that they are doing so

1470
00:57:02,870 --> 00:57:00,880
but i'm actually not aware right now of

1471
00:57:05,109 --> 00:57:02,880
anyone that's communicated to me that

1472
00:57:07,670 --> 00:57:05,119
they've made progress in particular the

1473
00:57:09,190 --> 00:57:07,680
three to one mean motion resonance uh is

1474
00:57:12,470 --> 00:57:09,200
still up in the air is it really a

1475
00:57:14,390 --> 00:57:12,480
resonance or has it is it not really a a

1476
00:57:16,549 --> 00:57:14,400
shepherding system and is the whole

1477
00:57:18,230 --> 00:57:16,559
system stable for all possible

1478
00:57:20,870 --> 00:57:18,240
eccentricities that you know within our

1479
00:57:23,030 --> 00:57:20,880
error bars or can you limit the the

1480
00:57:25,270 --> 00:57:23,040
orbital parameters by demanding

1481
00:57:26,710 --> 00:57:25,280
dynamical stability those questions are

1482
00:57:28,630 --> 00:57:26,720
still open

1483
00:57:31,109 --> 00:57:28,640
well the direction of my question was a

1484
00:57:33,109 --> 00:57:31,119
little broader uh it was in the more in

1485
00:57:33,910 --> 00:57:33,119
the context of

1486
00:57:35,589 --> 00:57:33,920
does

1487
00:57:38,470 --> 00:57:35,599
would you expect highly eccentric

1488
00:57:40,789 --> 00:57:38,480

systems to lead to uh

1489
00:57:42,549 --> 00:57:40,799
shorter lifetimes for potential

1490
00:57:44,150 --> 00:57:42,559
life-bearing planets and therefore

1491
00:57:47,030 --> 00:57:44,160
affect in a downward sense the

1492
00:57:49,109 --> 00:57:47,040
possibility of systems that might indeed

1493
00:57:51,990 --> 00:57:49,119
harbor life or where life might have

1494
00:57:54,150 --> 00:57:52,000
risen and prosper

1495
00:57:56,710 --> 00:57:54,160
uh i'm not you've asked

1496
00:57:58,789 --> 00:57:56,720
a number of interesting issues i think

1497
00:58:01,109 --> 00:57:58,799
my impression from the dynamicists is

1498
00:58:04,390 --> 00:58:01,119
that the dynamical evolution that leads

1499
00:58:06,549 --> 00:58:04,400
eventually to ejection of planets uh to

1500
00:58:08,549 --> 00:58:06,559
large eccentricities of planets that

1501
00:58:10,309 --> 00:58:08,559
happens relatively early on typically

1502
00:58:12,950 --> 00:58:10,319
within the first tens or

1503
00:58:15,109 --> 00:58:12,960
years uh tom quinn could perhaps talk

1504
00:58:16,630 --> 00:58:15,119
about this or jack lissauer

1505
00:58:18,390 --> 00:58:16,640
and it's certainly the case that when

1506
00:58:20,950 --> 00:58:18,400
you have a large planet of jupiter or

1507
00:58:22,789 --> 00:58:20,960
saturn size in an eccentric orbit it

1508
00:58:26,470 --> 00:58:22,799
renders any earth-like planets

1509
00:58:28,789 --> 00:58:26,480
vulnerable to uh being ejected by that

1510
00:58:30,870 --> 00:58:28,799
larger planet so there's no doubt at

1511
00:58:32,950 --> 00:58:30,880
this stage that planetary systems that

1512
00:58:33,910 --> 00:58:32,960
have even one planet in an eccentric

1513
00:58:36,309 --> 00:58:33,920

orbit

1514
00:58:45,270 --> 00:58:36,319
render the whole system i think less

1515
00:58:49,430 --> 00:58:47,670
jeff i'll add a question

1516
00:58:52,309 --> 00:58:49,440
do you think that there is an upper

1517
00:58:54,549 --> 00:58:52,319
limit to the mass of a bare rocky planet

1518
00:58:56,470 --> 00:58:54,559
either because of limits opposed by the

1519
00:58:58,390 --> 00:58:56,480
accretion itself or because when you get

1520
00:59:01,270 --> 00:58:58,400
above a certain size you started

1521
00:59:02,069 --> 00:59:01,280
creating ices or hydrogen helium on top

1522
00:59:03,109 --> 00:59:02,079
of it

1523
00:59:04,710 --> 00:59:03,119
yeah well

1524
00:59:06,870 --> 00:59:04,720
i don't know the answer to this and you

1525
00:59:09,190 --> 00:59:06,880
almost answered the question in your

1526
00:59:11,270 --> 00:59:09,200
posing of it uh it's certainly

1527
00:59:13,589 --> 00:59:11,280
probably the case that if you take a

1528
00:59:14,630 --> 00:59:13,599
typical protoplanetary disk the amount

1529
00:59:16,950 --> 00:59:14,640
of

1530
00:59:18,950 --> 00:59:16,960
refractory material that the heavier

1531
00:59:20,870 --> 00:59:18,960
elements is only going to get up to a

1532
00:59:23,109 --> 00:59:20,880
certain level maybe 10 or 15 earth

1533
00:59:24,870 --> 00:59:23,119
masses i would be very surprised if you

1534
00:59:26,789 --> 00:59:24,880
could make a rocky planet more than 10

1535
00:59:28,390 --> 00:59:26,799
or 15 earth masses partly because there

1536
00:59:30,470 --> 00:59:28,400
isn't much more rocky material in the

1537
00:59:32,470 --> 00:59:30,480
disk and also because of the issue you

1538
00:59:35,109 --> 00:59:32,480

raised that if you have that much rocky

1539
00:59:37,270 --> 00:59:35,119
material once it forms a core there's

1540
00:59:39,270 --> 00:59:37,280
probably still going to be some ices

1541
00:59:41,829 --> 00:59:39,280
around that will uh you know

1542
00:59:43,910 --> 00:59:41,839
gravitationally accumulate so roughly

1543
00:59:46,630 --> 00:59:43,920
speaking 10 earth masses is the number i

1544
00:59:53,510 --> 00:59:46,640
carry in my head but it's not based on

1545
00:59:57,030 --> 00:59:56,069
okay if we have any further questions on

1546
01:00:00,470 --> 00:59:57,040
the

1547
01:00:02,950 --> 01:00:00,480
hands on webex

1548
01:00:04,390 --> 01:00:02,960
and i'll just look around ames

1549
01:00:13,430 --> 01:00:04,400
and we have no further questions here in

1550
01:00:16,870 --> 01:00:15,430
please again look for the announcement

1551
01:00:19,510 --> 01:00:16,880
which will come out in a little while

1552
01:00:21,190 --> 01:00:19,520
about uh the seminar speakers for next

1553
01:00:23,670 --> 01:00:21,200
year and we'll pick up the seminar

1554
01:00:25,750 --> 01:00:23,680
series in uh the last week in january or

1555
01:00:28,710 --> 01:00:25,760
the first week in february the seminar

1556
01:00:33,030 --> 01:00:28,720
will take the holidays off see you all

1557
01:00:33,040 --> 01:00:36,950
uw did you have a question

1558
01:00:41,430 --> 01:00:39,190
i did actually uh

1559
01:00:43,510 --> 01:00:41,440
the second question was uh jeff when you

1560
01:00:45,829 --> 01:00:43,520
looked at the um

1561
01:00:47,270 --> 01:00:45,839
the mass distribution uh

1562
01:00:49,990 --> 01:00:47,280
n of m

1563
01:00:52,230 --> 01:00:50,000

what uh how carefully did you look at

1564
01:00:53,990 --> 01:00:52,240
the observational uh

1565
01:00:56,789 --> 01:00:54,000
or sorry the selection effects on how

1566
01:01:00,789 --> 01:00:56,799
that affects that slope right you had a

1567
01:01:03,750 --> 01:01:00,799
slope of m to the minus 1.1

1568
01:01:05,510 --> 01:01:03,760
uh yeah clearly the fact that you can't

1569
01:01:08,069 --> 01:01:05,520
get the smallest

1570
01:01:10,069 --> 01:01:08,079
planets affects that slope exactly right

1571
01:01:11,270 --> 01:01:10,079
and that's just what i was going to say

1572
01:01:13,109 --> 01:01:11,280
that

1573
01:01:15,190 --> 01:01:13,119
uh power law

1574
01:01:17,109 --> 01:01:15,200
has several flaws with it one is it

1575
01:01:19,750 --> 01:01:17,119
doesn't really fit the data so the power

1576
01:01:21,190 --> 01:01:19,760
law is not the right description uh

1577
01:01:23,510 --> 01:01:21,200
andrew has done a better

1578
01:01:26,230 --> 01:01:23,520
analysis and shows that a broken power

1579
01:01:28,549 --> 01:01:26,240
two power loss fits better suggesting

1580
01:01:31,589 --> 01:01:28,559
that it's it's steeper on the rocky

1581
01:01:33,750 --> 01:01:31,599
planet side but as you point out there's

1582
01:01:36,390 --> 01:01:33,760
great incompleteness for low masses

1583
01:01:38,069 --> 01:01:36,400
below a saturn mass we struggle to

1584
01:01:41,109 --> 01:01:38,079
detect those planets unless they're very

1585
01:01:43,270 --> 01:01:41,119
close in so the likelihood is that the

1586
01:01:45,670 --> 01:01:43,280
power law is even steeper

1587
01:01:48,309 --> 01:01:45,680
on the low mass end with much more many

1588
01:01:50,309 --> 01:01:48,319

more low mass planets uh relative to the

1589
01:01:53,750 --> 01:01:50,319
higher mass planets than we've detected

1590
01:01:56,630 --> 01:01:53,760
so the m to the minus one power law is

1591
01:02:00,789 --> 01:01:56,640
a simplistic empirical power law and

1592
01:02:05,829 --> 01:02:03,109
thanks has that cummins been work been

1593
01:02:07,670 --> 01:02:05,839
published no uh he's just finishing it

1594
01:02:09,670 --> 01:02:07,680
it's in referee right now so if you

1595
01:02:11,430 --> 01:02:09,680
email andrew coming i'm sure he'll send