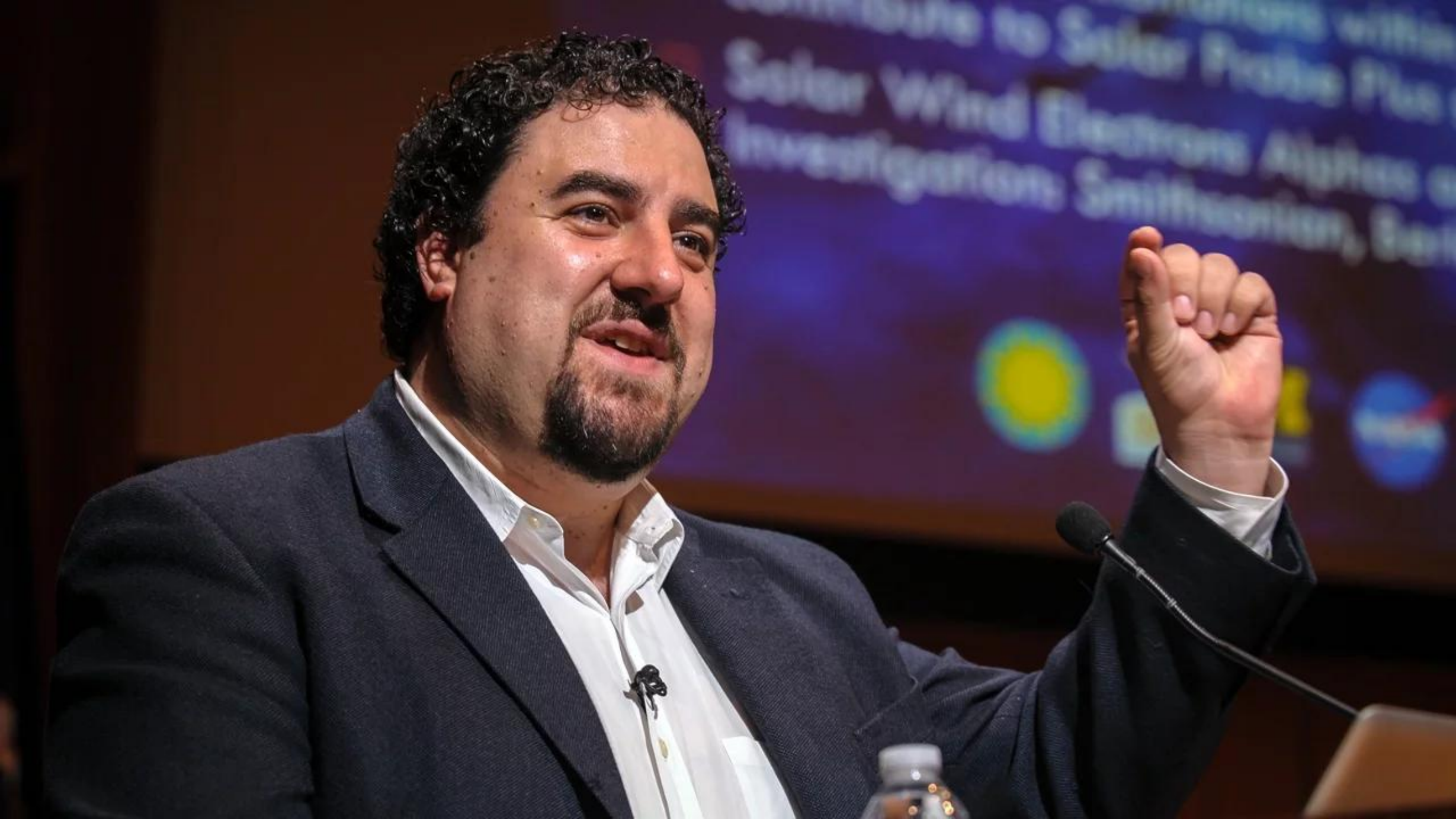

1
00:00:00,700 --> 00:00:06,700
[music playing]

2
00:00:17,133 --> 00:00:21,033
- Welcome to the 2015
NASA Ames Summer Series.

3
00:00:21,033 --> 00:00:24,733
In mission design, as in life,

4
00:00:24,733 --> 00:00:27,866
we tend to study lots of risks.

5
00:00:27,866 --> 00:00:30,433
But also,
as we design the mission,

6
00:00:30,433 --> 00:00:32,066
as we go through life,

7
00:00:32,066 --> 00:00:35,700
we also take certain items
for granted.

8
00:00:35,700 --> 00:00:38,400
Because we take them
for granted,

9
00:00:38,400 --> 00:00:41,066
usually they can develop

10
00:00:41,066 --> 00:00:44,433
into being a big risk.

11
00:00:44,433 --> 00:00:46,600
One such area
that we take for granted

12

00:00:46,600 --> 00:00:50,300
every single day is the sun.

13
00:00:50,300 --> 00:00:53,466
The sun is important for life.

14
00:00:53,466 --> 00:00:55,566
When we look
for habitable planets,

15
00:00:55,566 --> 00:00:57,300
we look at the energy

16
00:00:57,300 --> 00:01:01,100
that the star that the planet
surrounds creates

17
00:01:01,100 --> 00:01:03,733
to say, "Is it habitable?"

18
00:01:05,366 --> 00:01:07,400
In modern society,

19
00:01:07,400 --> 00:01:09,433
we have lots of things
that are dependent,

20
00:01:09,433 --> 00:01:10,633
lots of satellites,

21
00:01:10,633 --> 00:01:12,700
your TV, your GPS,

22
00:01:12,700 --> 00:01:16,366
that are dependent
on space assets.

23
00:01:16,366 --> 00:01:17,500
They're not protected

24
00:01:17,500 --> 00:01:20,066
by the atmosphere
that is here on Earth,

25
00:01:20,066 --> 00:01:23,566
so the sun
is critical for that area.

26
00:01:25,066 --> 00:01:26,733
Today's talk, entitled

27
00:01:26,733 --> 00:01:30,333
"Sending a Probe
Into the Atmosphere of Our Sun,"

28
00:01:30,333 --> 00:01:35,100
will be given
by Dr. Justin Kasper.

29
00:01:35,100 --> 00:01:37,300
Dr. Kasper
is an associate professor

30
00:01:37,300 --> 00:01:40,300
at the University of Michigan
and a researcher

31
00:01:40,300 --> 00:01:44,733
at the Smithsonian
Astrophysical Observatory.

32
00:01:44,733 --> 00:01:49,566
He earned an AB in Physics
from the University of Chicago

33
00:01:49,566 --> 00:01:52,666
and a PhD in Physics
from a small institute called

34
00:01:52,666 --> 00:01:56,366
the Massachusetts Institute
of Technology.

35
00:01:56,366 --> 00:01:59,700
He is the principal investigator
of the SWEAP Investigation,

36
00:01:59,700 --> 00:02:02,433
which you will hear about today.

37
00:02:02,433 --> 00:02:05,166
He also received, in 2010,

38
00:02:05,166 --> 00:02:07,600
the Presidential
Early Career Award

39
00:02:07,600 --> 00:02:10,400
for Scientists and Engineers,

40
00:02:10,400 --> 00:02:13,233
and in 2011...

41
00:02:13,233 --> 00:02:16,733
he was awarded
by "Popular Science" magazine

42
00:02:16,733 --> 00:02:19,866
as a Brilliant Ten to Watch For.

43
00:02:19,866 --> 00:02:23,400
Please join me in welcoming
Dr. Justin Kasper.

44
00:02:23,400 --> 00:02:26,400
[applause]

45

00:02:29,566 --> 00:02:30,900
- Thank you
for that introduction.

46
00:02:30,900 --> 00:02:32,000
It's great to be here.

47
00:02:32,000 --> 00:02:33,433
So what I want to do today

48
00:02:33,433 --> 00:02:35,600
is talk to you about our plans
to send a probe

49
00:02:35,600 --> 00:02:37,500
into the atmosphere
of our own sun.

50
00:02:37,500 --> 00:02:41,000
So, in three years,
actually, to the week,

51
00:02:41,000 --> 00:02:44,066
we're gonna make history
by sending an instrumented probe

52
00:02:44,066 --> 00:02:47,100
for the first time
into the atmosphere of our sun.

53
00:02:47,100 --> 00:02:50,300
This is going to enable us to
make unprecedented observations

54
00:02:50,300 --> 00:02:52,033
of the sun's atmosphere.

55
00:02:52,033 --> 00:02:53,766
It's also, obviously,

56
00:02:53,766 --> 00:02:55,366
an incredible technical
challenge,

57
00:02:55,366 --> 00:02:57,266
devising a spacecraft
and instruments

58
00:02:57,266 --> 00:02:59,066
that can survive
these close encounters

59
00:02:59,066 --> 00:03:00,666
with the sun.

60
00:03:00,666 --> 00:03:02,266
So what I want to do today

61
00:03:02,266 --> 00:03:06,266
is I want to give you a flavor
of the why and the how.

62
00:03:06,266 --> 00:03:10,533
So why are we building a probe
to enter the sun's atmosphere?

63
00:03:10,533 --> 00:03:12,933
What's so pressing?
Why do we need to do it now?

64
00:03:12,933 --> 00:03:14,500
What questions
are we trying to answer?

65
00:03:14,500 --> 00:03:16,133
And how are we gonna
go about doing it?

66
00:03:16,133 --> 00:03:19,266

At a closest approach,
the front of the spacecraft

67
00:03:19,266 --> 00:03:23,000
is gonna be absorbing megawatts
of sunlight from the sun.

68
00:03:23,000 --> 00:03:27,000
Exposed surfaces will be heated
to 1,500 degrees Celsius.

69
00:03:27,000 --> 00:03:28,733
The whole front
of the spacecraft

70
00:03:28,733 --> 00:03:29,933
and sun-exposed instruments

71
00:03:29,933 --> 00:03:33,433
will actually
be glowing red to the eye.

72
00:03:33,433 --> 00:03:35,033
So that's obviously

73
00:03:35,033 --> 00:03:37,266
a very unusual environment
for a spacecraft.

74
00:03:37,266 --> 00:03:39,366
It's not like anything
we've had to deal with before,

75
00:03:39,366 --> 00:03:40,966
and so this presents

76
00:03:40,966 --> 00:03:42,933
certain very specific
technical challenges,

77
00:03:42,933 --> 00:03:46,033
including how do you convince
yourself that your design

78
00:03:46,033 --> 00:03:48,733
for an object that can actually
survive that environment

79
00:03:48,733 --> 00:03:51,000
is gonna actually work?

80
00:03:51,000 --> 00:03:54,100
Now, before I get
into the why and the how,

81
00:03:54,100 --> 00:03:57,566
I do want to spend a little bit
of time talking about the who.

82
00:03:57,566 --> 00:04:00,866
So, you know, I'm here today
to talk about Solar Probe,

83
00:04:00,866 --> 00:04:03,266
but I'm just one of many people
working on this project.

84
00:04:03,266 --> 00:04:06,400
There are hundreds and hundreds
of scientists, engineers,

85
00:04:06,400 --> 00:04:08,466
and supporting staff
across the country

86
00:04:08,466 --> 00:04:10,900
that are responsible
for this amazing mission

87

00:04:10,900 --> 00:04:13,533
that I'm fortunate enough to get
to talk to you about today.

88
00:04:13,533 --> 00:04:15,266
If you're curious,

89
00:04:15,266 --> 00:04:17,000
Solar Probe
is part of what we call

90
00:04:17,000 --> 00:04:19,400
the Living With a Star
Program at NASA.

91
00:04:19,400 --> 00:04:21,233
The mission itself is led

92
00:04:21,233 --> 00:04:23,600
by Johns Hopkins University's
Applied Physics lab,

93
00:04:23,600 --> 00:04:25,466
and the Living
With a Star Program

94
00:04:25,466 --> 00:04:27,900
is coordinated with
Goddard Space Flight Center.

95
00:04:27,900 --> 00:04:29,833
But there are more than
40 institutions

96
00:04:29,833 --> 00:04:31,533
that are playing a role
in the science

97
00:04:31,533 --> 00:04:34,366
and the instrumentation

and the observing plans

98
00:04:34,366 --> 00:04:37,400
and in the theory
that we need for this mission.

99
00:04:37,400 --> 00:04:38,900
My part of the project

100
00:04:38,900 --> 00:04:41,166
is called the Solar Wind
Electrons Alphas and Protons,

101
00:04:41,166 --> 00:04:43,066
or SWEAP, Investigation.

102
00:04:43,066 --> 00:04:44,500
It turns out
the solar atmosphere

103
00:04:44,500 --> 00:04:47,466
is predominantly made of fully
ionized hydrogen and helium,

104
00:04:47,466 --> 00:04:50,066
or the slang for that
is alphas and protons.

105
00:04:50,066 --> 00:04:52,333
So electrons, alphas,
and protons

106
00:04:52,333 --> 00:04:53,533
are our bread and butter,

107
00:04:53,533 --> 00:04:55,500
and that's what
our investigation is measuring.

108

00:04:55,500 --> 00:04:57,166
And that part of the project

109
00:04:57,166 --> 00:05:01,000
we lead out of the Smithsonian
Astrophysical Observatory,

110
00:05:01,000 --> 00:05:04,400
Berkeley Space Sciences Lab,
relatively nearby,

111
00:05:04,400 --> 00:05:06,566
University of Michigan, NASA,

112
00:05:06,566 --> 00:05:08,833
and other partners
around the country.

113
00:05:08,833 --> 00:05:11,033
So I'll be telling you
about this project,

114
00:05:11,033 --> 00:05:14,166
and I'll just give you my little
particular sliver of experience.

115
00:05:14,166 --> 00:05:16,366
There's a lot of amazing stuff
going on on Probe.

116
00:05:16,366 --> 00:05:17,500
So let's start with the why.

117
00:05:17,500 --> 00:05:20,200
Why send a probe
into the atmosphere of the sun?

118
00:05:20,200 --> 00:05:22,300
And, you know,
here's a photograph

119
00:05:22,300 --> 00:05:23,933
of a base camp at Everest.

120
00:05:23,933 --> 00:05:26,233
I know the first thought might
be, "Well, why not?" right?

121
00:05:26,233 --> 00:05:29,666
Isn't part
of NASA's responsibility,

122
00:05:29,666 --> 00:05:31,066
isn't what we're interested in

123
00:05:31,066 --> 00:05:34,333
just to go new places, you know,
to do things that are hard?

124
00:05:34,333 --> 00:05:37,200
There are definitely a lot
of very hard aspects

125
00:05:37,200 --> 00:05:39,000
to a solar probe mission.

126
00:05:39,000 --> 00:05:40,066
It's very exciting.

127
00:05:40,066 --> 00:05:41,900
I really enjoy
getting to tell people

128
00:05:41,900 --> 00:05:43,366
about all the new technology

129
00:05:43,366 --> 00:05:45,900
we've had to develop
just to do this mission.

130
00:05:45,900 --> 00:05:47,866
But that's not the only reason
we're doing this.

131
00:05:47,866 --> 00:05:51,200
There are some very basic
scientific motivations,

132
00:05:51,200 --> 00:05:53,000
some scientific puzzles

133
00:05:53,000 --> 00:05:56,200
that have actually been around
for more than 500 years,

134
00:05:56,200 --> 00:05:59,000
though only really appreciated
in the last 100 years,

135
00:05:59,000 --> 00:06:03,533
and then with our new dependence
on infrastructure in space,

136
00:06:03,533 --> 00:06:05,833
our sensitivity
to space weather,

137
00:06:05,833 --> 00:06:08,400
unfortunately,
these mysteries about the sun

138
00:06:08,400 --> 00:06:10,266
can now influence society
on Earth,

139
00:06:10,266 --> 00:06:11,800
and so it's become
very pressing

140
00:06:11,800 --> 00:06:13,200
that we launch this probe.

141
00:06:13,200 --> 00:06:16,200
So, beyond just the thrill
of exploration,

142
00:06:16,200 --> 00:06:19,133
we have some very basic
scientific reasons.

143
00:06:19,133 --> 00:06:21,266
So let's start with the why,

144
00:06:21,266 --> 00:06:26,000
and here's a picture taken by
the Solar Dynamics Observatory,

145
00:06:26,000 --> 00:06:28,900
in visible light of the sun
a couple years ago,

146
00:06:28,900 --> 00:06:30,300
and so here's the sun.

147
00:06:30,300 --> 00:06:31,966
It's yellow,
kind of boring, right?

148
00:06:31,966 --> 00:06:35,300
You know,
just this yellow sphere.

149
00:06:35,300 --> 00:06:38,300
It doesn't seem particularly
dynamic or interesting, right?

150
00:06:38,300 --> 00:06:43,000
If you went out on any day,

this is what you'd see, right?

151
00:06:43,000 --> 00:06:45,900
Now, why is the surface
of the sun yellow, right?

152
00:06:45,900 --> 00:06:48,000
It's yellow
because it's at a temperature

153
00:06:48,000 --> 00:06:50,566
of around 6,000 degrees Kelvin,

154
00:06:50,566 --> 00:06:53,266
So, if you look at your toaster

155
00:06:53,266 --> 00:06:55,933
and you get those heating
elements nice and hot,

156
00:06:55,933 --> 00:06:59,200
they'll start glowing a yellow,
an orange, right?

157
00:06:59,200 --> 00:07:01,333
This is called
black-body radiation.

158
00:07:01,333 --> 00:07:04,900
So every object
in the universe emits radiation,

159
00:07:04,900 --> 00:07:06,566
and the wavelength
of the radiation

160
00:07:06,566 --> 00:07:09,000
is inversely proportional to
the temperature of the object.

161
00:07:09,000 --> 00:07:11,933
So right now if I had, like,
infrared goggles on,

162
00:07:11,933 --> 00:07:14,800
I could see everyone in the room
just from the infrared light

163
00:07:14,800 --> 00:07:17,333
that you're giving off 'cause
your body's at room temperature.

164
00:07:17,333 --> 00:07:19,000
If you get hotter,

165
00:07:19,000 --> 00:07:20,433
you'll actually start
to emit visible light,

166
00:07:20,433 --> 00:07:22,100
so you move from infrared

167
00:07:22,100 --> 00:07:26,066
into very dull reds,
darker reds, yellows--

168
00:07:26,066 --> 00:07:28,133
sorry, oranges,
and then yellows.

169
00:07:28,133 --> 00:07:32,000
And so the surface
of the sun glows yellow

170
00:07:32,000 --> 00:07:35,166
because it's at a temperature
of around 6,000 degrees.

171
00:07:35,166 --> 00:07:37,366

What you're seeing
is the end product of the fusion

172
00:07:37,366 --> 00:07:39,266
happening at the core
of the sun.

173
00:07:39,266 --> 00:07:42,866
So, at the center of the sun
the pressure is so high,

174
00:07:42,866 --> 00:07:46,300
the density's so high
that hydrogen fuses,

175
00:07:46,300 --> 00:07:49,133
making helium, releasing energy.

176
00:07:49,133 --> 00:07:51,133
That brings the temperature
of the core of the sun

177
00:07:51,133 --> 00:07:54,000
up to more than
100 million degrees.

178
00:07:54,000 --> 00:07:56,233
And then just the further away
you get from that heat source,

179
00:07:56,233 --> 00:07:57,833
the same way, you know,

180
00:07:57,833 --> 00:08:00,200
if you pull your hand
away from an open flame,

181
00:08:00,200 --> 00:08:01,400
the cooler things get.

182
00:08:01,400 --> 00:08:03,100
The temperature
slowly falls off

183
00:08:03,100 --> 00:08:05,033
the further away
you get from the sun

184
00:08:05,033 --> 00:08:06,800
until you're out at the surface

185
00:08:06,800 --> 00:08:10,333
where things are a relatively
balmy 6,000 degrees,

186
00:08:10,333 --> 00:08:12,566
and the only exceptions--

187
00:08:12,566 --> 00:08:15,733
just if you look carefully,
you'll see every now and then,

188
00:08:15,733 --> 00:08:18,333
there are some black splotches
that appear on the sun.

189
00:08:18,333 --> 00:08:20,200
These are sunspots.

190
00:08:20,200 --> 00:08:23,500
Here's a nice zoom-in
of one of these sunspots,

191
00:08:23,500 --> 00:08:25,166
and what you see
is a darker region.

192
00:08:25,166 --> 00:08:28,300
It turns out every now and then,

a big piece

193
00:08:28,300 --> 00:08:31,266
of magnetic field erupts
from the surface of the sun,

194
00:08:31,266 --> 00:08:33,100
and that magnetic field
is so strong,

195
00:08:33,100 --> 00:08:36,833
it actually stops the sun
from boiling and churning there,

196
00:08:36,833 --> 00:08:39,166
and that piece of the sun's
atmosphere cools off,

197
00:08:39,166 --> 00:08:40,766
and so it looks dark to us

198
00:08:40,766 --> 00:08:43,133
'cause it's not giving off
that black-body radiation.

199
00:08:43,133 --> 00:08:45,300
So sunspots are fantastic,

200
00:08:45,300 --> 00:08:48,166
but is this all
there is to the sun?

201
00:08:48,166 --> 00:08:51,233
And the answer is gonna be no.

202
00:08:51,233 --> 00:08:54,500
So, you know, it's difficult
to look at the sun, right?

203

00:08:54,500 --> 00:08:56,466
You know, I don't want to
encourage anyone to go out there

204
00:08:56,466 --> 00:08:58,100
and stare at the sun right now.

205
00:08:58,100 --> 00:08:59,433
You know, it's so bright,
it can blind you.

206
00:08:59,433 --> 00:09:01,400
If you wear filters,

207
00:09:01,400 --> 00:09:05,000
you can look at the disc
of the sun in visible light.

208
00:09:05,000 --> 00:09:06,833
But what you really want to do

209
00:09:06,833 --> 00:09:08,333
to understand the mystery
of the sun

210
00:09:08,333 --> 00:09:12,266
is to be able to get a chance
to see what's above the surface.

211
00:09:12,266 --> 00:09:15,000
Is there anything
going on out here, right?

212
00:09:15,000 --> 00:09:17,300
Today we can look
with spacecraft

213
00:09:17,300 --> 00:09:20,900
that have special filters
that block the disc of the sun

214
00:09:20,900 --> 00:09:22,333
or look in wavelengths

215
00:09:22,333 --> 00:09:24,900
that are much brighter than
emission from the sun itself.

216
00:09:24,900 --> 00:09:28,000
But if you went back
500 years ago,

217
00:09:28,000 --> 00:09:30,533
you had to wait
for a particular alignment.

218
00:09:30,533 --> 00:09:34,566
So this is a painting
from 1570

219
00:09:34,566 --> 00:09:37,366
titled "Astronomers Observing
an Eclipse,"

220
00:09:37,366 --> 00:09:39,500
and what they were taking
advantage of

221
00:09:39,500 --> 00:09:41,566
is the fact that the moon

222
00:09:41,566 --> 00:09:43,566
is almost the exact
same angular diameter

223
00:09:43,566 --> 00:09:44,966
of the sun in the sky.

224
00:09:44,966 --> 00:09:46,166

It's the size of your thumb

225
00:09:46,166 --> 00:09:47,733
if you stretch your arm
out all the way,

226
00:09:47,733 --> 00:09:49,000
about 1/2 a degree.

227
00:09:49,000 --> 00:09:51,400
And so, if you wait just
for the right time

228
00:09:51,400 --> 00:09:53,400
and you're in the right place
on Earth,

229
00:09:53,400 --> 00:09:54,833
for about five, ten minutes,

230
00:09:54,833 --> 00:09:58,066
the moon will pass
between you and the sun.

231
00:09:58,066 --> 00:10:00,000
You'll have an artificial night

232
00:10:00,000 --> 00:10:02,133
where the center
of the sun is blocked out.

233
00:10:02,133 --> 00:10:06,166
And if you're patient,
your eyes adapt to the dark,

234
00:10:06,166 --> 00:10:09,900
an atmosphere will start
to appear around the sun,

235

00:10:09,900 --> 00:10:12,200
much fainter than the surface
of the sun itself,

236
00:10:12,200 --> 00:10:13,800
so normally invisible.

237
00:10:13,800 --> 00:10:16,533
And even in old paintings
and old records

238
00:10:16,533 --> 00:10:19,133
from 500 years ago,
1,000 years ago,

239
00:10:19,133 --> 00:10:21,866
people commented
about how during an eclipse

240
00:10:21,866 --> 00:10:24,266
they were able to see
rays of material

241
00:10:24,266 --> 00:10:26,400
coming out from around the sun.

242
00:10:26,400 --> 00:10:29,466
And so they called these rays
a solar crown,

243
00:10:29,466 --> 00:10:32,800
and another word for crown,
it was in Latin,

244
00:10:32,800 --> 00:10:35,133
it was the solar corona,
and this stuck.

245
00:10:35,133 --> 00:10:37,533
So, to this day

we call the solar atmosphere,

246
00:10:37,533 --> 00:10:39,033
the extended solar atmosphere,

247
00:10:39,033 --> 00:10:42,933
the solar corona to indicate
the ray-like structure,

248
00:10:42,933 --> 00:10:45,366
and I'll show you
some nice examples of that soon.

249
00:10:45,366 --> 00:10:47,200
Okay, so here's

250
00:10:47,200 --> 00:10:49,333
how you could observe the sun's
atmosphere 500 years ago.

251
00:10:49,333 --> 00:10:52,000
What can we do today?

252
00:10:52,000 --> 00:10:55,366
Here's an eclipse seen from
the International Space Station

253
00:10:55,366 --> 00:10:58,133
over Turkey in March of 2006.

254
00:10:58,133 --> 00:11:00,966
So this is a photograph
taken by an astronaut

255
00:11:00,966 --> 00:11:03,966
looking down on the surface
of the Earth

256
00:11:03,966 --> 00:11:07,166

just as the shadow cast
by the moon blocking the sun

257
00:11:07,166 --> 00:11:08,500
passes over Turkey.

258
00:11:08,500 --> 00:11:11,200
And now I'm gonna show you
a photograph of the sun

259
00:11:11,200 --> 00:11:14,366
taken at the exact same instant
in time by some astronomers

260
00:11:14,366 --> 00:11:16,400
in the center of that shadow,

261
00:11:16,400 --> 00:11:20,000
looking now up past
the Space Station at the sun.

262
00:11:22,166 --> 00:11:24,200
Okay, and so, if you squint,

263
00:11:24,200 --> 00:11:28,233
you may just be able to make out
some craters on the moon.

264
00:11:28,233 --> 00:11:31,200
The moon's doing a perfect job
blocking out the sun,

265
00:11:31,200 --> 00:11:35,166
and instead of the very
intense light from the sun,

266
00:11:35,166 --> 00:11:37,866
we see these rays
of material appear.

267
00:11:37,866 --> 00:11:40,366
So this is the solar atmosphere,
the solar corona.

268
00:11:40,366 --> 00:11:42,866
And maybe you can see why,

269
00:11:42,866 --> 00:11:45,133
you know,
back in the Renaissance times

270
00:11:45,133 --> 00:11:47,400
people called this
the solar crown,

271
00:11:47,400 --> 00:11:49,533
this ray-like structure.

272
00:11:49,533 --> 00:11:52,100
And you can see
it's a couple things.

273
00:11:52,100 --> 00:11:54,166
One, it's
incredibly structured.

274
00:11:54,166 --> 00:11:55,433
You know, you have some places

275
00:11:55,433 --> 00:11:58,933
where you just have rays
of material coming straight out.

276
00:11:58,933 --> 00:12:01,966
You have other regions
where it bunches together.

277
00:12:01,966 --> 00:12:05,033
If you're interested, what we're

actually witnessing here

278
00:12:05,033 --> 00:12:06,933
is Thomson scattering of light,

279
00:12:06,933 --> 00:12:09,933
so white light
from the sun is travelling out.

280
00:12:09,933 --> 00:12:12,200
It's striking material
in the solar corona,

281
00:12:12,200 --> 00:12:14,200
and then that light
bounces off.

282
00:12:14,200 --> 00:12:16,333
And so we're able to see
that reflected light

283
00:12:16,333 --> 00:12:18,466
off of the material
in the solar atmosphere.

284
00:12:18,466 --> 00:12:20,433
It's not actually emitting
in visible light.

285
00:12:20,433 --> 00:12:23,533
It's just reflecting
visible light from the sun.

286
00:12:23,533 --> 00:12:24,866
Okay, great.

287
00:12:24,866 --> 00:12:27,266
So people commented
about these rays

288
00:12:27,266 --> 00:12:29,900
for hundreds of years.

289
00:12:29,900 --> 00:12:32,066
It's interesting--the sun
has an extended atmosphere.

290
00:12:32,066 --> 00:12:33,933
So what, right?

291
00:12:33,933 --> 00:12:38,400
Well, the scale height
of that corona is a big problem,

292
00:12:38,400 --> 00:12:40,033
although people didn't really
appreciate this

293
00:12:40,033 --> 00:12:43,000
until halfway
through the 19th century

294
00:12:43,000 --> 00:12:45,066
around the American Civil War

295
00:12:45,066 --> 00:12:47,533
where the concept of heat
was first discovered

296
00:12:47,533 --> 00:12:49,833
and thermodynamics.

297
00:12:49,833 --> 00:12:52,100
Whoops, my equation
isn't showing up there.

298
00:12:52,100 --> 00:12:54,400
Well, I can walk you
through this.

299
00:12:54,400 --> 00:12:56,433
So, if we assume
the sun's atmosphere

300
00:12:56,433 --> 00:12:59,966
was in simple, isothermal,
hydrostatic equilibrium--

301
00:12:59,966 --> 00:13:02,400
so all at one temperature,

302
00:13:02,400 --> 00:13:04,400
you know,
it's nice and symmetric.

303
00:13:04,400 --> 00:13:06,133
This is like
the-cow-is-a-sphere level

304
00:13:06,133 --> 00:13:08,966
of approximations
that physicists like to do.

305
00:13:08,966 --> 00:13:12,300
What you can do is
you can derive an expression

306
00:13:12,300 --> 00:13:15,366
for how quickly the density
of the solar atmosphere

307
00:13:15,366 --> 00:13:17,433
should fall off with altitude,

308
00:13:17,433 --> 00:13:18,900
the same way
Earth's atmosphere--

309

00:13:18,900 --> 00:13:21,466
You get in an airplane,
you go up to higher altitudes,

310
00:13:21,466 --> 00:13:23,900
the pressure gets lower
and lower and lower, right?

311
00:13:23,900 --> 00:13:26,200
Well, you can derive
the scale height

312
00:13:26,200 --> 00:13:29,966
at which Earth's atmosphere
should half and then half again

313
00:13:29,966 --> 00:13:32,833
and then half again
just based on the mass

314
00:13:32,833 --> 00:13:35,266
of the typical molecule
in our atmosphere

315
00:13:35,266 --> 00:13:36,400
and local gravity.

316
00:13:36,400 --> 00:13:39,366
You can do the same thing
with the sun,

317
00:13:39,366 --> 00:13:43,033
and if you plug in
the sun's gravity,

318
00:13:43,033 --> 00:13:46,300
which people had a good idea of
even 150 years ago,

319
00:13:46,300 --> 00:13:49,100

and you plug in
the 6,000-degree temperature

320
00:13:49,100 --> 00:13:51,000
of the surface of the sun,

321
00:13:51,000 --> 00:13:52,833
you get
that the sun's atmosphere

322
00:13:52,833 --> 00:13:56,400
should fall off
in half in density

323
00:13:56,400 --> 00:13:58,400
every 100 kilometers or so.

324
00:13:58,400 --> 00:14:00,200
All right,
that's a real problem,

325
00:14:00,200 --> 00:14:02,800
because if you look
at these photographs,

326
00:14:02,800 --> 00:14:05,000
this material falls off,
you know.

327
00:14:05,000 --> 00:14:06,833
You're still seeing a lot
of material

328
00:14:06,833 --> 00:14:08,866
an entire solar radii away,
you know,

329
00:14:08,866 --> 00:14:11,366
even 4 or 5 solar radii away,

330
00:14:11,366 --> 00:14:14,833
about 1,000 times greater scale

331
00:14:14,833 --> 00:14:17,200
than a simple model
would predict.

332
00:14:17,200 --> 00:14:19,900
Right, so there are only two
possible conclusions, then,

333
00:14:19,900 --> 00:14:22,233
if you use the simple model
of an atmosphere.

334
00:14:22,233 --> 00:14:24,833
Either the sun's corona

335
00:14:24,833 --> 00:14:28,233
is 1,000 times hotter
than the surface of the sun,

336
00:14:28,233 --> 00:14:32,200
or the sun's atmosphere is made
out of some new form of matter

337
00:14:32,200 --> 00:14:34,033
never before seen on Earth

338
00:14:34,033 --> 00:14:37,066
that weighs 1,000 times
less than any normal matter

339
00:14:37,066 --> 00:14:39,000
that we've ever found on Earth.

340
00:14:39,000 --> 00:14:41,400
So, at the beginning
of the 20th century,

341
00:14:41,400 --> 00:14:43,200
people said,
"Well, it's preposterous

342
00:14:43,200 --> 00:14:45,300
that the atmosphere
could be hotter.

343
00:14:45,300 --> 00:14:47,366
You know, we all know things
get cooler the further away

344
00:14:47,366 --> 00:14:48,866
you get from a heat source.

345
00:14:48,866 --> 00:14:50,233
So there must be a new form
of matter."

346
00:14:50,233 --> 00:14:51,533
And they called it coronium

347
00:14:51,533 --> 00:14:53,333
because it was what
the solar corona was made of.

348
00:14:53,333 --> 00:14:55,700
And for a long time,
people were trying to hunt

349
00:14:55,700 --> 00:14:58,200
for evidence
of coronium.

350
00:14:58,200 --> 00:14:59,900
It was only in the 1930s,

351
00:14:59,900 --> 00:15:02,000

as we started understanding
the physics

352
00:15:02,000 --> 00:15:05,500
of high-temperature materials
and techniques

353
00:15:05,500 --> 00:15:08,200
such as atomic spectroscopy,
that we finally realized

354
00:15:08,200 --> 00:15:10,800
that there isn't
a new form of matter.

355
00:15:10,800 --> 00:15:12,400
Actually, what's happening is,

356
00:15:12,400 --> 00:15:14,633
through some process
that we still don't understand,

357
00:15:14,633 --> 00:15:16,566
the solar corona is heated

358
00:15:16,566 --> 00:15:19,400
to temperatures of 1 million
to 10 million degrees,

359
00:15:19,400 --> 00:15:22,400
so thousands of times hotter
than the surface of the sun.

360
00:15:22,400 --> 00:15:24,966
That whole concept
that we normally have

361
00:15:24,966 --> 00:15:26,566
that we're comfortable with
on Earth

362
00:15:26,566 --> 00:15:28,500
where the further away
you are from a heat source,

363
00:15:28,500 --> 00:15:29,800
the cooler things get

364
00:15:29,800 --> 00:15:31,966
seems to break down
in the solar atmosphere.

365
00:15:31,966 --> 00:15:35,833
Things reverse,
and the temperature shoots up.

366
00:15:35,833 --> 00:15:38,066
Now, instead of waiting
for an eclipse,

367
00:15:38,066 --> 00:15:40,266
what we can do today
is we can use a spacecraft

368
00:15:40,266 --> 00:15:42,733
like the
Solar Dynamics Observatory

369
00:15:42,733 --> 00:15:44,033
and look at the sun

370
00:15:44,033 --> 00:15:46,533
not in visible light
but in ultraviolet light.

371
00:15:46,533 --> 00:15:49,233
So, as I said before,
this black-body radiation,

372

00:15:49,233 --> 00:15:51,166
the hotter an object is,

373
00:15:51,166 --> 00:15:53,900
the shorter and shorter
a wavelength it emits at.

374
00:15:53,900 --> 00:15:57,233
I said that this white light
from the solar eclipse

375
00:15:57,233 --> 00:15:59,800
is not actually light given off
by material in the corona.

376
00:15:59,800 --> 00:16:02,233
It's reflected light
from the sun.

377
00:16:02,233 --> 00:16:05,733
The corona is pretty much
invisible to our eyes.

378
00:16:05,733 --> 00:16:08,366
You need to be able to see
in ultraviolet light.

379
00:16:08,366 --> 00:16:11,466
You need to see in wavelengths
corresponding to material

380
00:16:11,466 --> 00:16:13,233
that's heated
to half a million degrees,

381
00:16:13,233 --> 00:16:14,833
a million degrees

382
00:16:14,833 --> 00:16:18,300
before the corona

actually appears directly.

383
00:16:18,300 --> 00:16:20,933
So this is a month
of observations

384
00:16:20,933 --> 00:16:24,333
taken by
the Solar Dynamics Observatory.

385
00:16:24,333 --> 00:16:28,333
We're looking at a wavelength
of light that's 171 angstroms.

386
00:16:28,333 --> 00:16:31,000
It corresponds to plasma
in the solar corona

387
00:16:31,000 --> 00:16:32,300
that's been heated
to a temperature

388
00:16:32,300 --> 00:16:34,333
of about half a million degrees.

389
00:16:34,333 --> 00:16:39,133
And so what you can see is far
from a boring, simple sphere,

390
00:16:39,133 --> 00:16:41,300
the sun
has an incredibly structured,

391
00:16:41,300 --> 00:16:43,933
incredibly dynamic atmosphere.

392
00:16:43,933 --> 00:16:46,200
I'll just highlight
a couple features here.

393
00:16:46,200 --> 00:16:49,500
Can you see these loops, right?

394
00:16:49,500 --> 00:16:51,066
And the loops are moving around,

395
00:16:51,066 --> 00:16:52,733
but they seem to pop up
from one place

396
00:16:52,733 --> 00:16:53,966
and come down to another.

397
00:16:53,966 --> 00:16:57,166
So what you're seeing
is a magnetic field

398
00:16:57,166 --> 00:16:59,566
that emerges from one sunspot,

399
00:16:59,566 --> 00:17:01,566
travels across the surface
of the sun,

400
00:17:01,566 --> 00:17:04,100
and then descends down
into another sunspot.

401
00:17:04,100 --> 00:17:07,100
And the reason we're able to
see it is million-degree plasma

402
00:17:07,100 --> 00:17:09,933
is stuck
on those magnetic field lines.

403
00:17:09,933 --> 00:17:12,933
Think of it as like when you
look at a neon sign, right?

404
00:17:12,933 --> 00:17:15,366
You can trace out a message
in glass,

405
00:17:15,366 --> 00:17:17,366
and you fill the glass
with a hot plasma

406
00:17:17,366 --> 00:17:19,233
that glows in visible light.

407
00:17:19,233 --> 00:17:21,033
Same thing's happening here.

408
00:17:21,033 --> 00:17:23,800
Somehow, and we don't really
understand how,

409
00:17:23,800 --> 00:17:26,500
the magnetic field
that emerges from sunspots

410
00:17:26,500 --> 00:17:29,900
is really good at heating plasma
up to very high temperatures.

411
00:17:29,900 --> 00:17:33,033
It introduces magnetic fields
into the sun's atmosphere,

412
00:17:33,033 --> 00:17:34,800
and that has something
to do with the heating

413
00:17:34,800 --> 00:17:36,066
of the solar atmosphere

414
00:17:36,066 --> 00:17:38,500

and how the solar atmosphere
gets its structure.

415
00:17:38,500 --> 00:17:40,100
And you can see
it's very dynamic.

416
00:17:40,100 --> 00:17:43,166
You can see things
are popping around constantly.

417
00:17:43,166 --> 00:17:45,933
New loops emerge.
Loops disappear.

418
00:17:45,933 --> 00:17:48,933
There's a lot
of activity going on.

419
00:17:48,933 --> 00:17:51,833
Okay, so, by the 1930s,
people realized--

420
00:17:51,833 --> 00:17:54,033
even if they didn't know
how the sun's atmosphere

421
00:17:54,033 --> 00:17:56,566
is heated 1,000 times
hotter than the surface,

422
00:17:56,566 --> 00:17:59,833
they accepted that it was at
1 million to 10 million degrees.

423
00:17:59,833 --> 00:18:02,033
But it was only
in the 1950s

424
00:18:02,033 --> 00:18:04,733

that a theorist named
Gene Parker realized

425
00:18:04,733 --> 00:18:06,966
that, actually,
it's incredibly unstable

426
00:18:06,966 --> 00:18:08,800
to heat the atmosphere of a star

427
00:18:08,800 --> 00:18:10,566
up to these very high
temperatures.

428
00:18:10,566 --> 00:18:13,200
In fact, if you look
at those high temperatures,

429
00:18:13,200 --> 00:18:15,733
they're gonna want to push
the star's atmosphere

430
00:18:15,733 --> 00:18:17,366
away from the surface.

431
00:18:17,366 --> 00:18:20,300
Now, gravity's gonna fight and
try to contain that atmosphere,

432
00:18:20,300 --> 00:18:23,833
but what Parker showed
is actually there's a regime

433
00:18:23,833 --> 00:18:26,800
of star masses and gravity

434
00:18:26,800 --> 00:18:30,233
and temperatures
where the atmosphere

435
00:18:30,233 --> 00:18:33,900
not only wants to expand out
but that expansion's unstable.

436
00:18:33,900 --> 00:18:36,333
So the further
away from the star

437
00:18:36,333 --> 00:18:39,933
that the corona expands,
the faster it starts moving.

438
00:18:39,933 --> 00:18:41,133
It accelerates.

439
00:18:41,133 --> 00:18:43,433
So this was a plot
from Parker's paper,

440
00:18:43,433 --> 00:18:46,466
speed as a function of height
above the surface of the sun.

441
00:18:46,466 --> 00:18:50,033
Once you're a few solar radii
above the sun,

442
00:18:50,033 --> 00:18:51,233
this plasma is flowing

443
00:18:51,233 --> 00:18:54,200
at a couple hundred kilometers
per second.

444
00:18:54,200 --> 00:18:55,833
It breaks the speed of sound.

445
00:18:55,833 --> 00:18:59,233
I'll break it to you--

there is sound in space.

446
00:18:59,233 --> 00:19:02,500
The density's incredibly low,
so the speeds are very high,

447
00:19:02,500 --> 00:19:05,533
many hundreds
of kilometers per second.

448
00:19:05,533 --> 00:19:07,500
But the plasma
breaks the speed of sound

449
00:19:07,500 --> 00:19:09,333
within a couple solar radii.

450
00:19:09,333 --> 00:19:13,433
By 10 solar radii, it's flowing
faster than the fastest waves

451
00:19:13,433 --> 00:19:15,000
that can travel in a plasma,

452
00:19:15,000 --> 00:19:17,833
special magnetized waves
we call Alfven waves,

453
00:19:17,833 --> 00:19:20,400
and by the time
you're out at 1 au,

454
00:19:20,400 --> 00:19:22,733
you have a plasma
that's flowing

455
00:19:22,733 --> 00:19:25,966
at about 10 to 20 times the
speed of sound through space.

456
00:19:25,966 --> 00:19:28,300
And Parker
called this a solar wind.

457
00:19:28,300 --> 00:19:30,233
And no one believed him.

458
00:19:30,233 --> 00:19:32,400
Paper kept getting rejected.

459
00:19:32,400 --> 00:19:33,833
Finally, an astronomer

460
00:19:33,833 --> 00:19:36,433
who was editing
the Astrophysical Journal,

461
00:19:36,433 --> 00:19:38,900
which is where he published this
paper, said, "You know what?

462
00:19:38,900 --> 00:19:41,066
Like, it's better
to have a controversy out there.

463
00:19:41,066 --> 00:19:43,566
No one believes it, but no one
can find an error in the math.

464
00:19:43,566 --> 00:19:44,900
Let's get it out there."

465
00:19:44,900 --> 00:19:47,533
Within a few years,
the Space Age had started.

466
00:19:47,533 --> 00:19:50,466
Rockets had made it
outside of Earth's atmosphere,

467
00:19:50,466 --> 00:19:53,400
and the solar wind
was detected.

468
00:19:53,400 --> 00:19:56,066
Now, today I can actually
show you the solar wind,

469
00:19:56,066 --> 00:19:58,033
because we don't have to wait
for lunar eclipses anymore.

470
00:19:58,033 --> 00:20:01,800
We can actually go up into orbit
around Earth

471
00:20:01,800 --> 00:20:05,066
and use special cameras
with little filters

472
00:20:05,066 --> 00:20:06,733
that block the sun itself,

473
00:20:06,733 --> 00:20:10,533
so we can take
eclipse images 24/7.

474
00:20:10,533 --> 00:20:14,300
And this is an example
of a month of solar eclipses.

475
00:20:14,300 --> 00:20:18,233
What you can see in this image,
this is not actually blue light.

476
00:20:18,233 --> 00:20:19,866
The space isn't blue.

477

00:20:19,866 --> 00:20:21,833
We're just coloring it blue
'cause it looks nice.

478
00:20:21,833 --> 00:20:23,266
The diameter of the sun

479
00:20:23,266 --> 00:20:26,166
is indicated
by this white circle here.

480
00:20:26,166 --> 00:20:29,066
Here's a baffle that's blocking
light from near the sun.

481
00:20:29,066 --> 00:20:30,800
And what you're seeing
is material

482
00:20:30,800 --> 00:20:33,233
streaming away from the sun
in different directions.

483
00:20:33,233 --> 00:20:36,366
And so, if you concentrate
in any one direction,

484
00:20:36,366 --> 00:20:38,100
you can see
that there's this jet

485
00:20:38,100 --> 00:20:40,200
of material moving away
at pretty high speeds.

486
00:20:40,200 --> 00:20:43,300
You can see the motion of it
expanding away from the sun.

487
00:20:43,300 --> 00:20:46,933

You can also see
that it's incredibly structured.

488
00:20:46,933 --> 00:20:49,266
Can you see the stars
moving behind the sun?

489
00:20:49,266 --> 00:20:51,333
To give you a sense
of timescale,

490
00:20:51,333 --> 00:20:53,500
it takes, you know,

491
00:20:53,500 --> 00:20:56,366
a year for the Earth
to go around the sun,

492
00:20:56,366 --> 00:21:01,333
and so, you know,
in 365 days we move 360 degrees,

493
00:21:01,333 --> 00:21:04,033
or we move around the sun
about a degree per day.

494
00:21:04,033 --> 00:21:07,233
So if you look at these stars
in the background,

495
00:21:07,233 --> 00:21:08,400
in the time it takes them

496
00:21:08,400 --> 00:21:10,233
to get from this side
of the sun to the other,

497
00:21:10,233 --> 00:21:12,300
that's about a day.

498
00:21:13,900 --> 00:21:16,000
And so you can see
there are jets of material.

499
00:21:16,000 --> 00:21:17,366
There are periods
where the--

500
00:21:17,366 --> 00:21:19,066
regions
where there's less material.

501
00:21:19,066 --> 00:21:20,433
Then every now and then,

502
00:21:20,433 --> 00:21:22,233
although never when I say
to look at it--

503
00:21:22,233 --> 00:21:24,966
Oh, there we go.
There's a big one up there.

504
00:21:24,966 --> 00:21:26,366
You'll get a giant eruption.

505
00:21:26,366 --> 00:21:29,033
Oh, there we go here.
There's a nice one there.

506
00:21:29,033 --> 00:21:31,466
We call these coronal mass
ejections,

507
00:21:31,466 --> 00:21:35,333
something like a billion,
billion tons of material

508
00:21:35,333 --> 00:21:36,966

flying away from the sun

509
00:21:36,966 --> 00:21:40,133
at a couple thousand kilometers
per second.

510
00:21:40,133 --> 00:21:42,400
These numbers really
don't make much sense, right?

511
00:21:42,400 --> 00:21:43,933
They're not very intuitive.

512
00:21:43,933 --> 00:21:46,200
That's fast enough to get
from New York to LA

513
00:21:46,200 --> 00:21:48,066
in a couple seconds.

514
00:21:48,066 --> 00:21:52,066
And it's enough material
that if it happens to hit Earth,

515
00:21:52,066 --> 00:21:55,066
it can actually cause
our entire magnetosphere,

516
00:21:55,066 --> 00:21:57,366
the magnetic field
that surrounds the Earth,

517
00:21:57,366 --> 00:21:59,566
to ring like a struck bell

518
00:21:59,566 --> 00:22:02,833
and generate all sorts
of disturbances on Earth.

519

00:22:02,833 --> 00:22:05,566
Aircraft lose radio
communication.

520
00:22:05,566 --> 00:22:10,133
GPS transmitters
are off by meters,

521
00:22:10,133 --> 00:22:11,900
sometimes even kilometers,

522
00:22:11,900 --> 00:22:14,366
because their signal paths
are distorted.

523
00:22:14,366 --> 00:22:16,466
And, unfortunately,
your cell phone,

524
00:22:16,466 --> 00:22:18,466
your GPS receiver in your car

525
00:22:18,466 --> 00:22:21,133
doesn't yet know to tell you,

526
00:22:21,133 --> 00:22:23,166
"Hey, there's a solar flare
going on,

527
00:22:23,166 --> 00:22:24,933
so maybe you
shouldn't trust my directions

528
00:22:24,933 --> 00:22:26,466
for the next few hours."
Right?

529
00:22:26,466 --> 00:22:28,466
So, if you're trying
to land an airplane,

530
00:22:28,466 --> 00:22:30,800
if you're trying
to deliver a package

531
00:22:30,800 --> 00:22:32,233
and you're trying
to find the right address,

532
00:22:32,233 --> 00:22:34,933
you really care
about that GPS working,

533
00:22:34,933 --> 00:22:37,366
and you should be very worried
about those periods where

534
00:22:37,366 --> 00:22:41,233
we lose navigational capability
due to these storms.

535
00:22:43,100 --> 00:22:46,000
Now, I showed you those coronal
mass ejections flying out,

536
00:22:46,000 --> 00:22:48,333
and I just want to show you
one more example looking close

537
00:22:48,333 --> 00:22:49,933
into the beginning of a CME.

538
00:22:49,933 --> 00:22:52,066
Look right here.

539
00:22:52,066 --> 00:22:54,900
Boom.

540
00:22:54,900 --> 00:22:57,233

All right, so that's
a coronal mass ejection

541
00:22:57,233 --> 00:22:59,300
erupting from the surface
of the sun.

542
00:22:59,300 --> 00:23:03,033
This color image is not actual
natural color of the sun.

543
00:23:03,033 --> 00:23:04,533
What we've done here
is we've taken

544
00:23:04,533 --> 00:23:06,800
three ultraviolet wavelengths

545
00:23:06,800 --> 00:23:08,433
and converted them
into red, green, and blue

546
00:23:08,433 --> 00:23:10,000
just to give you a sense

547
00:23:10,000 --> 00:23:11,233
of the different temperatures
of material

548
00:23:11,233 --> 00:23:13,133
in the solar atmosphere.

549
00:23:13,133 --> 00:23:15,666
What I'm gonna do is I'm gonna
replay that one

550
00:23:15,666 --> 00:23:18,166
just 'cause
I think it's really cool.

551
00:23:18,166 --> 00:23:20,400
And what I want you to pay
attention for,

552
00:23:20,400 --> 00:23:22,233
just for kicks
so you can appreciate

553
00:23:22,233 --> 00:23:24,066
these coronal mass ejections--

554
00:23:24,066 --> 00:23:26,333
First of all,
just watch how quickly

555
00:23:26,333 --> 00:23:30,866
it goes from no motion at all
to this giant eruption.

556
00:23:30,866 --> 00:23:32,133
By the way,
each frame in that image

557
00:23:32,133 --> 00:23:34,266
was taken ten seconds apart,

558
00:23:34,266 --> 00:23:36,566
to give you a sense
of timescale.

559
00:23:36,566 --> 00:23:39,366
Also, if you look very closely
as it erupts out,

560
00:23:39,366 --> 00:23:43,000
you can actually see a shockwave
form and expand across the sun.

561
00:23:43,000 --> 00:23:44,366

It's that shockwave

562
00:23:44,366 --> 00:23:46,566
that goes out in front
of the coronal mass ejection

563
00:23:46,566 --> 00:23:49,500
that can hit Earth and cause
the initial disruption.

564
00:23:49,500 --> 00:23:51,466
But that blob
that comes flying out

565
00:23:51,466 --> 00:23:53,333
carries strong magnetic fields,

566
00:23:53,333 --> 00:23:56,733
and it can wreak havoc
on objects like Earth for days.

567
00:23:56,733 --> 00:23:58,733
All right, let's replay that.

568
00:24:10,866 --> 00:24:14,500
We would love to be able
to look at these images

569
00:24:14,500 --> 00:24:17,933
and say that an eruption
like that is gonna happen.

570
00:24:17,933 --> 00:24:20,066
We don't know
how to do that yet, right?

571
00:24:20,066 --> 00:24:23,266
NOAA has a space weather
prediction center.

572
00:24:23,266 --> 00:24:26,833
NASA's very hard at work,
scientists around the country,

573
00:24:26,833 --> 00:24:29,166
at developing ways to look
at measurements like this

574
00:24:29,166 --> 00:24:30,566
and be able to say,

575
00:24:30,566 --> 00:24:32,900
"Hey, in an hour, there's gonna
be a big eruption."

576
00:24:32,900 --> 00:24:34,566
Even if we could say,
you know,

577
00:24:34,566 --> 00:24:37,033
"30 minutes beforehand,
there's gonna be a big flare..."

578
00:24:37,033 --> 00:24:39,300
We can't even say
after one of these eruptions

579
00:24:39,300 --> 00:24:41,000
whether or not
it's gonna hit Earth

580
00:24:41,000 --> 00:24:42,166
and, if it does hit Earth,

581
00:24:42,166 --> 00:24:43,966
whether or not it's gonna
cause a problem.

582
00:24:43,966 --> 00:24:45,833

So there are a lot of gaps
in our knowledge

583
00:24:45,833 --> 00:24:49,233
and our ability
to predict these events.

584
00:24:49,233 --> 00:24:52,733
So...

585
00:24:52,733 --> 00:24:56,166
that's the why.

586
00:24:56,166 --> 00:24:59,766
Let's talk about the objectives
of Solar Probe

587
00:24:59,766 --> 00:25:02,833
to try to answer--address all
these mysteries I'm showing you,

588
00:25:02,833 --> 00:25:04,333
and then we'll talk
about the how.

589
00:25:04,333 --> 00:25:06,500
So the overarching goal
of Solar Probe is,

590
00:25:06,500 --> 00:25:08,000
"To determine the structure

591
00:25:08,000 --> 00:25:10,233
and dynamics of the sun's
coronal magnetic field,

592
00:25:10,233 --> 00:25:11,866
understand how the solar corona

593

00:25:11,866 --> 00:25:13,533
and wind
are heated and accelerated,

594
00:25:13,533 --> 00:25:15,400
and determine
what mechanisms accelerate

595
00:25:15,400 --> 00:25:17,200
and transport
energetic particles."

596
00:25:17,200 --> 00:25:18,433
It's a little longwinded,

597
00:25:18,433 --> 00:25:20,900
but it's distilled
into three objectives.

598
00:25:20,900 --> 00:25:22,266
One, we want to see

599
00:25:22,266 --> 00:25:24,833
how the energy is flowing
from the sun into the corona

600
00:25:24,833 --> 00:25:25,900
and out into space.

601
00:25:25,900 --> 00:25:28,100
Two, we want to figure out

602
00:25:28,100 --> 00:25:31,000
how that incredible structure
is created by magnetic fields.

603
00:25:31,000 --> 00:25:32,500
And three,
we want to figure out

604
00:25:32,500 --> 00:25:36,066
how those coronal mass ejections
are accelerated to high speeds.

605
00:25:36,066 --> 00:25:38,866
And it's been 50 years-plus

606
00:25:38,866 --> 00:25:40,466
since the beginning
of space exploration.

607
00:25:40,466 --> 00:25:43,166
We have beautiful imagery
from 1 au.

608
00:25:43,166 --> 00:25:46,366
We actually can sample
the solar wind from spacecraft

609
00:25:46,366 --> 00:25:48,466
near Earth and elsewhere
in the solar system.

610
00:25:48,466 --> 00:25:50,666
But we still have not been
able to figure out

611
00:25:50,666 --> 00:25:52,000
what's heating the atmosphere,

612
00:25:52,000 --> 00:25:53,566
what's accelerating
these particles.

613
00:25:53,566 --> 00:25:56,100
To do that
we need to send a probe

614
00:25:56,100 --> 00:25:57,533

into the sun's atmosphere

615
00:25:57,533 --> 00:25:59,433
and directly measure
what's going on.

616
00:25:59,433 --> 00:26:01,000
How fast
are the particles moving?

617
00:26:01,000 --> 00:26:02,866
How hot are they getting?

618
00:26:02,866 --> 00:26:05,200
Is it magnetic fields
that's heating the particles?

619
00:26:05,200 --> 00:26:08,133
Is it mechanical waves coming
from the surface of the sun?

620
00:26:08,133 --> 00:26:10,400
If we could just go there
and measure these quantities,

621
00:26:10,400 --> 00:26:11,666
we could figure out

622
00:26:11,666 --> 00:26:15,000
what's actually driving
all these phenomena.

623
00:26:15,000 --> 00:26:18,200
So the overall objective
of Solar Probe is to get

624
00:26:18,200 --> 00:26:21,133
down within 10 solar radii
of the surface of the sun.

625
00:26:21,133 --> 00:26:22,933
Just to put that
in perspective,

626
00:26:22,933 --> 00:26:26,066
Earth orbits
about 214 solar radii

627
00:26:26,066 --> 00:26:27,166
away from the sun.

628
00:26:27,166 --> 00:26:29,733
So we want to be just about 4%

629
00:26:29,733 --> 00:26:31,233
above the surface of the sun,

630
00:26:31,233 --> 00:26:35,000
deep in those eclipse images
that I showed you earlier.

631
00:26:35,000 --> 00:26:36,900
I won't go
into great detail here,

632
00:26:36,900 --> 00:26:38,366
but this is just a plot

633
00:26:38,366 --> 00:26:41,400
of what we think the typical
speed of the solar wind is

634
00:26:41,400 --> 00:26:44,433
as a function of height
above the surface of the sun.

635
00:26:44,433 --> 00:26:47,800
And then I'll just point out
this is height in solar radii,

636
00:26:47,800 --> 00:26:49,900
and it's
in a logarithmic scale.

637
00:26:49,900 --> 00:26:51,500
This is speed
in kilometers per second,

638
00:26:51,500 --> 00:26:54,066
also in a logarithmic scale.

639
00:26:54,066 --> 00:26:58,233
And so this is what we think

640
00:26:58,233 --> 00:27:02,000
the fastest wave
in the solar corona moves at

641
00:27:02,000 --> 00:27:03,800
as a function of height
above the sun--

642
00:27:03,800 --> 00:27:06,400
usually these magnetic waves
or Alfven waves.

643
00:27:06,400 --> 00:27:10,133
Close to the sun, they can move
at extremely high speeds.

644
00:27:10,133 --> 00:27:13,066
Turns out the further
you get away from the sun,

645
00:27:13,066 --> 00:27:15,866
these waves' speeds drop down.

646
00:27:15,866 --> 00:27:19,333

Somewhere above 10,
maybe 20 solar radii,

647
00:27:19,333 --> 00:27:22,366
there are no longer any waves
that can travel from the sun

648
00:27:22,366 --> 00:27:23,733
into that solar wind.

649
00:27:23,733 --> 00:27:25,200
We want to get
below that point.

650
00:27:25,200 --> 00:27:27,266
We want to get into a region

651
00:27:27,266 --> 00:27:29,500
that's still interacting
with the surface of the sun

652
00:27:29,500 --> 00:27:32,300
so we can tell what kind of
waves are in the solar corona.

653
00:27:32,300 --> 00:27:36,266
So that intersection
sets the target for Solar Probe.

654
00:27:36,266 --> 00:27:39,100
We want to get
below 10 solar radii.

655
00:27:39,100 --> 00:27:42,500
Our goal is actually
9.86 solar radii.

656
00:27:42,500 --> 00:27:45,466
Just to put things
in perspective, here's Earth.

657
00:27:45,466 --> 00:27:47,866
Here's how close we've gotten
to the sun before.

658
00:27:47,866 --> 00:27:50,700
So we'll be going
about 7 times closer

659
00:27:50,700 --> 00:27:54,000
than anyone
ever has in the past.

660
00:27:54,000 --> 00:27:55,300
Our timeline--

661
00:27:55,300 --> 00:27:57,166
we had what's called
our critical design review

662
00:27:57,166 --> 00:27:59,900
back in March of this year.

663
00:27:59,900 --> 00:28:02,866
Our schedule has us launching
in July of 2018

664
00:28:02,866 --> 00:28:04,966
on a Delta-IV Heavy.

665
00:28:04,966 --> 00:28:06,433
Now, this is interesting.

666
00:28:06,433 --> 00:28:08,300
We launch in July of 2018.

667
00:28:08,300 --> 00:28:10,533
We're actually gonna have our
first encounter with the sun--

668
00:28:10,533 --> 00:28:13,433
although it's all the way
out at 34 solar radii,

669
00:28:13,433 --> 00:28:16,466
that'll still be closer than
we've ever gotten before--

670
00:28:16,466 --> 00:28:18,900
in October of 2018,

671
00:28:18,900 --> 00:28:21,566
Halloween, to be specific.

672
00:28:21,566 --> 00:28:24,900
And then we're going
to slowly get closer to the sun,

673
00:28:24,900 --> 00:28:29,566
and we'll have our final
closest approach in 2024.

674
00:28:31,166 --> 00:28:33,200
So how do we get
close to the surface of the sun?

675
00:28:33,200 --> 00:28:35,900
It turns out that Earth

676
00:28:35,900 --> 00:28:37,933
is moving way too fast
around the sun

677
00:28:37,933 --> 00:28:39,833
for it to be easy
to get close to the sun.

678
00:28:39,833 --> 00:28:41,533

We have too much
angular momentum,

679
00:28:41,533 --> 00:28:43,166
so we're gonna put Solar Probe--

680
00:28:43,166 --> 00:28:45,566
which is actually one of the
smaller spacecraft we ever made.

681
00:28:45,566 --> 00:28:47,833
It weighs around 600 kilograms.

682
00:28:47,833 --> 00:28:50,066
We're gonna put it
on the largest rocket

683
00:28:50,066 --> 00:28:52,233
currently available,
a Delta-IV Heavy,

684
00:28:52,233 --> 00:28:54,233
and that's gonna
get the spacecraft

685
00:28:54,233 --> 00:28:57,533
escaping from Earth
as fast as we possibly can.

686
00:28:57,533 --> 00:28:59,466
That's still not fast enough.

687
00:28:59,466 --> 00:29:01,166
Instead,
what we're gonna do

688
00:29:01,166 --> 00:29:03,866
is about two months
after launch,

689
00:29:03,866 --> 00:29:05,333
Solar Probe is gonna hurtle

690
00:29:05,333 --> 00:29:09,033
just 100 kilometers over
the surface of Venus, right?

691
00:29:09,033 --> 00:29:12,500
We're gonna actually speed
Venus up just a little bit.

692
00:29:12,500 --> 00:29:13,800
No one will notice.

693
00:29:13,800 --> 00:29:16,166
Venus is gonna slow
the spacecraft down

694
00:29:16,166 --> 00:29:18,833
and bend its orbit
towards the sun.

695
00:29:18,833 --> 00:29:22,333
And that's what lets us achieve
our first encounter

696
00:29:22,333 --> 00:29:24,933
at 35 solar radii.

697
00:29:24,933 --> 00:29:26,133
Over the next five years,

698
00:29:26,133 --> 00:29:28,900
we'll continue to trade
momentum with Venus.

699
00:29:28,900 --> 00:29:30,900
So we have a series--

700
00:29:30,900 --> 00:29:33,366
This is just a plot
of our distance from the sun

701
00:29:33,366 --> 00:29:35,233
as a function of time.

702
00:29:35,233 --> 00:29:38,100
We have three encounters
at 35 solar radii.

703
00:29:38,100 --> 00:29:40,833
We go past Venus.
That brings us closer.

704
00:29:40,833 --> 00:29:41,900
Another Venus encounter,

705
00:29:41,900 --> 00:29:44,233
another, another,
another, another,

706
00:29:44,233 --> 00:29:46,400
slowly letting us
walk closer and closer

707
00:29:46,400 --> 00:29:47,866
to the surface of the sun,

708
00:29:47,866 --> 00:29:50,500
culminating in the final phase
of our mission

709
00:29:50,500 --> 00:29:54,366
in the 2024 timeframe
at 10 solar radii.

710
00:29:59,066 --> 00:30:00,366
Oops.

711
00:30:00,366 --> 00:30:02,766
All right, one of these images
isn't rendering.

712
00:30:02,766 --> 00:30:04,266
Well, I'll tell you
a little bit

713
00:30:04,266 --> 00:30:06,233
about prior versions
of the spacecraft,

714
00:30:06,233 --> 00:30:08,233
and then I have plenty
of examples

715
00:30:08,233 --> 00:30:10,833
of the current version of
the spacecraft in later slides.

716
00:30:10,833 --> 00:30:13,400
So people have been talking
about a solar probe, actually,

717
00:30:13,400 --> 00:30:15,866
before NASA even existed.

718
00:30:15,866 --> 00:30:19,000
Since we knew
about the solar wind

719
00:30:19,000 --> 00:30:20,500
and we knew about
the solar corona,

720
00:30:20,500 --> 00:30:22,533
it seemed, you know,
like a no-brainer.

721
00:30:22,533 --> 00:30:25,033
If we're gonna be able
to send instruments into space,

722
00:30:25,033 --> 00:30:27,100
let's visit
our sun's atmosphere.

723
00:30:27,100 --> 00:30:29,133
It turns out it's very hard
to design a probe

724
00:30:29,133 --> 00:30:30,933
to enter the sun's atmosphere.

725
00:30:30,933 --> 00:30:33,400
So, over the years,
every decade or so,

726
00:30:33,400 --> 00:30:36,000
there'd be
a new design iteration.

727
00:30:36,000 --> 00:30:37,900
I'm particularly fond
of this one.

728
00:30:37,900 --> 00:30:41,400
It had a giant,
sort of surfboard-shaped

729
00:30:41,400 --> 00:30:42,966
carbon foam heat shield

730
00:30:42,966 --> 00:30:45,033
that would have doubled
as a high-gain antenna

731
00:30:45,033 --> 00:30:48,400

to transmit signals
back to Earth--

732
00:30:48,400 --> 00:30:50,200
that early solar probe.

733
00:30:50,200 --> 00:30:53,966
And then the solar probe
from around the year 2000

734
00:30:53,966 --> 00:30:56,400
would have actually gone
all the way out to Jupiter,

735
00:30:56,400 --> 00:30:59,533
used Jupiter to completely slow
the spacecraft down,

736
00:30:59,533 --> 00:31:01,433
and then just basically
plummeted down

737
00:31:01,433 --> 00:31:03,100
and plunged through
the sun's atmosphere

738
00:31:03,100 --> 00:31:05,266
once at about 4 solar radii.

739
00:31:05,266 --> 00:31:06,866
And then if it survived,

740
00:31:06,866 --> 00:31:10,033
five years later,
it could go again.

741
00:31:10,033 --> 00:31:12,833
Ironically, those probes
got too close to the sun

742
00:31:12,833 --> 00:31:14,266
to use solar power.

743
00:31:14,266 --> 00:31:16,133
The panels would melt.

744
00:31:16,133 --> 00:31:19,300
So they were powered
by plutonium the same way--

745
00:31:19,300 --> 00:31:23,400
like outer planet missions
like the Voyagers are powered.

746
00:31:25,366 --> 00:31:28,433
The new solar probe, the one
that we're actually designing

747
00:31:28,433 --> 00:31:32,000
and building, uses this concept
of the Venus encounter,

748
00:31:32,000 --> 00:31:34,066
so we don't have
to go out to Jupiter.

749
00:31:34,066 --> 00:31:36,066
We don't get quite as close.

750
00:31:36,066 --> 00:31:38,366
We only get into,
like, 9 1/2 solar radii,

751
00:31:38,366 --> 00:31:41,733
so we're able to use
solar power.

752
00:31:41,733 --> 00:31:43,400
And I'll just show you

some highlights

753
00:31:43,400 --> 00:31:44,733
of the spacecraft here

754
00:31:44,733 --> 00:31:46,800
and then talk a little bit
about the implementation.

755
00:31:46,800 --> 00:31:49,900
So the main thing
that'll draw your eye

756
00:31:49,900 --> 00:31:51,266
that's different
between Solar Probe

757
00:31:51,266 --> 00:31:54,000
and a lot of other missions
is this front part.

758
00:31:54,000 --> 00:31:56,466
This is our thermal protection
system, or heat shield.

759
00:31:56,466 --> 00:31:59,300
It's made out of a material
called carbon foam.

760
00:31:59,300 --> 00:32:01,400
It's extremely light,

761
00:32:01,400 --> 00:32:03,066
and it's
an incredible insulator.

762
00:32:03,066 --> 00:32:05,366
At closest approach,
the front of the carbon foam

763
00:32:05,366 --> 00:32:07,966
will be
at about 1,500 degrees Celsius.

764
00:32:07,966 --> 00:32:10,366
The back will be
at about 300 degrees Celsius.

765
00:32:10,366 --> 00:32:13,866
It's only, like,
6 inches thick.

766
00:32:13,866 --> 00:32:16,500
The rest of the spacecraft,
generally speaking,

767
00:32:16,500 --> 00:32:18,500
hides behind this heat shield.

768
00:32:18,500 --> 00:32:21,666
We have a bunch
of long titanium struts,

769
00:32:21,666 --> 00:32:23,400
and then the rest
of the spacecraft's

770
00:32:23,400 --> 00:32:25,533
sort of held back
from the heat shield.

771
00:32:25,533 --> 00:32:27,200
We have solar panels,

772
00:32:27,200 --> 00:32:29,333
and I'll show you
the solar panels come out

773
00:32:29,333 --> 00:32:31,166

the further away we are
from the sun.

774
00:32:31,166 --> 00:32:33,000
And then the closer we get
and the hotter things get

775
00:32:33,000 --> 00:32:35,433
and the brighter the sun gets,
they bend backwards.

776
00:32:35,433 --> 00:32:37,233
So when we're encountering
the sun,

777
00:32:37,233 --> 00:32:39,166
just the very edges
of the solar panels

778
00:32:39,166 --> 00:32:41,266
are peeking out from the side
of the heat shield.

779
00:32:41,266 --> 00:32:44,966
That's more than enough sunlight
to power the spacecraft.

780
00:32:44,966 --> 00:32:47,066
Those solar panels
are gonna get hot,

781
00:32:47,066 --> 00:32:48,266
so we need to have a way
to cool them off.

782
00:32:48,266 --> 00:32:50,166
So what we actually do

783
00:32:50,166 --> 00:32:53,100
is pump water

through the solar panels, right?

784
00:32:53,100 --> 00:32:56,433
That water then flows
into these large radiators.

785
00:32:56,433 --> 00:32:59,800
Think of it as the radiator
on your car...

786
00:32:59,800 --> 00:33:01,866
with one
important exception.

787
00:33:01,866 --> 00:33:03,633
When you're driving
on the highway,

788
00:33:03,633 --> 00:33:06,200
air blows
across your radiator, right?

789
00:33:06,200 --> 00:33:09,233
Or if you have the CPU
in your laptop gets hot,

790
00:33:09,233 --> 00:33:11,233
maybe you have a little fan
that turns on

791
00:33:11,233 --> 00:33:12,800
to help it
cool off a little better.

792
00:33:12,800 --> 00:33:15,100
Well, there are
no fans in space.

793
00:33:15,100 --> 00:33:16,666
You just have to rely

on the fact

794
00:33:16,666 --> 00:33:18,833
that space itself
is extremely cold,

795
00:33:18,833 --> 00:33:20,400
and you radiate heat away.

796
00:33:20,400 --> 00:33:22,366
So we need very large panels

797
00:33:22,366 --> 00:33:25,100
that we pump the water through
to keep it cool.

798
00:33:25,100 --> 00:33:27,733
Interestingly,
when we're far from the sun,

799
00:33:27,733 --> 00:33:29,066
we have the opposite problem.

800
00:33:29,066 --> 00:33:30,400
The water would want to freeze.

801
00:33:30,400 --> 00:33:32,066
So one of the reasons
the solar panels

802
00:33:32,066 --> 00:33:34,233
are all the way out
when we're far from the sun

803
00:33:34,233 --> 00:33:36,566
is to warm the water
in the radiator system

804
00:33:36,566 --> 00:33:38,200

to keep it
from getting too cold.

805
00:33:38,200 --> 00:33:41,100
The whole spacecraft regulates
its own body temperature

806
00:33:41,100 --> 00:33:44,233
almost like a mammal would.

807
00:33:44,233 --> 00:33:46,200
So, when we launch,

808
00:33:46,200 --> 00:33:48,133
we'll immediately deploy
the solar panels.

809
00:33:48,133 --> 00:33:51,133
We've got instruments bristling
all over the spacecraft.

810
00:33:51,133 --> 00:33:53,200
There's a telescope
that's gonna take images

811
00:33:53,200 --> 00:33:56,900
looking out
from the side of the spacecraft.

812
00:33:56,900 --> 00:34:00,433
Here's one
of my instruments here.

813
00:34:00,433 --> 00:34:02,900
We're gonna sense
very precisely

814
00:34:02,900 --> 00:34:05,566
the magnetic fields
from the sun.

815
00:34:05,566 --> 00:34:07,566
Unfortunately,
we don't want to measure--

816
00:34:07,566 --> 00:34:09,266
well, we don't want to report
back the magnetic field

817
00:34:09,266 --> 00:34:10,566
of the spacecraft,

818
00:34:10,566 --> 00:34:13,866
so we need to put that
on the end of a very large boom

819
00:34:13,866 --> 00:34:17,233
to get it as far away
from the spacecraft as possible.

820
00:34:17,233 --> 00:34:19,966
Once we've completed
that initial deployment,

821
00:34:19,966 --> 00:34:21,900
those are
all the mechanical moving parts,

822
00:34:21,900 --> 00:34:23,333
and we can begin
our commissioning

823
00:34:23,333 --> 00:34:25,900
and solar encounters.

824
00:34:25,900 --> 00:34:27,066
My instrument suite--

825
00:34:27,066 --> 00:34:29,833

I won't go
into this in great detail,

826
00:34:29,833 --> 00:34:33,033
but one instrument
which I'm gonna talk to you

827
00:34:33,033 --> 00:34:36,200
a little bit about now
is called the Solar Probe Cup,

828
00:34:36,200 --> 00:34:39,200
and then our other instruments
sit in the shadow here and here.

829
00:34:39,200 --> 00:34:41,833
And their role on this mission

830
00:34:41,833 --> 00:34:44,966
is to sweep up ions
and electrons

831
00:34:44,966 --> 00:34:47,100
and look at the directions
they're coming from,

832
00:34:47,100 --> 00:34:49,433
how fast they're moving,
how many of them there are,

833
00:34:49,433 --> 00:34:52,266
and let us read out
and report back to Earth,

834
00:34:52,266 --> 00:34:54,200
like, things like the density,

835
00:34:54,200 --> 00:34:56,100
temperature, pressure,

836
00:34:56,100 --> 00:34:57,866
velocity,

837
00:34:57,866 --> 00:34:59,966
flow angles
of the solar wind, right?

838
00:34:59,966 --> 00:35:01,466
We want to be able
to see, you know,

839
00:35:01,466 --> 00:35:03,166
how fast is the wind going?

840
00:35:03,166 --> 00:35:04,866
Which way is it flowing?

841
00:35:04,866 --> 00:35:06,533
How much helium
is there in the solar wind?

842
00:35:06,533 --> 00:35:08,333
How much is that varying?

843
00:35:08,333 --> 00:35:10,866
And if you think back
to those movies

844
00:35:10,866 --> 00:35:12,533
of the coronagraph
that I showed you,

845
00:35:12,533 --> 00:35:15,300
the solar wind
tends to flow away from the sun.

846
00:35:15,300 --> 00:35:18,233
So one of our challenges
on this mission is,

847
00:35:18,233 --> 00:35:20,100
you know, 90% of the time,

848
00:35:20,100 --> 00:35:21,866
the wind isn't gonna be coming
at an angle.

849
00:35:21,866 --> 00:35:24,033
It's gonna be flowing
straight away from the sun.

850
00:35:24,033 --> 00:35:26,333
So, if we want to capture
that solar wind

851
00:35:26,333 --> 00:35:29,100
and see how hot it is
and what direction it's flowing,

852
00:35:29,100 --> 00:35:30,333
how dense it is,

853
00:35:30,333 --> 00:35:32,566
we need to be able
to look straight at the sun.

854
00:35:32,566 --> 00:35:35,233
So, in addition
to some very sensitive,

855
00:35:35,233 --> 00:35:38,233
sophisticated instruments
that sit in the shadow,

856
00:35:38,233 --> 00:35:41,233
we also had to come up
with a very robust instrument

857

00:35:41,233 --> 00:35:43,533
that could actually sample
the solar wind

858
00:35:43,533 --> 00:35:47,300
while exposed to levels
of sunlight

859
00:35:47,300 --> 00:35:50,866
about 500 times brighter than
what you'd experience on Earth.

860
00:35:50,866 --> 00:35:53,400
The front of the instrument
will actually be glowing red hot

861
00:35:53,400 --> 00:35:55,400
during each of the encounters.

862
00:35:57,066 --> 00:35:59,033
And I think
we have a little animation here

863
00:35:59,033 --> 00:36:02,100
of what we've gotten
ourselves into.

864
00:36:02,100 --> 00:36:05,533
So there's the Solar Probe Cup,

865
00:36:05,533 --> 00:36:08,400
and so it's designed
to collect samples

866
00:36:08,400 --> 00:36:11,100
of solar wind flowing
straight away from the sun

867
00:36:11,100 --> 00:36:14,366
as we near--

as we go throughout our orbit.

868
00:36:14,366 --> 00:36:17,233
As you can see from here,
the rest of the instruments,

869
00:36:17,233 --> 00:36:19,900
the solar panels
nicely tuck back

870
00:36:19,900 --> 00:36:23,400
so they're not exposed
to the sunlight.

871
00:36:25,100 --> 00:36:27,466
So I'll just end now
with a little bit

872
00:36:27,466 --> 00:36:29,533
about the Solar Probe Cup.

873
00:36:29,533 --> 00:36:33,033
It's one of my instruments, so
I'll show you some baby pictures

874
00:36:33,033 --> 00:36:37,133
and just give you a sense
of some of the thrill,

875
00:36:37,133 --> 00:36:38,966
some of the challenges
and the excitement

876
00:36:38,966 --> 00:36:42,000
of coming up with
and then demonstrating

877
00:36:42,000 --> 00:36:44,233
an instrument like this
can actually survive

878
00:36:44,233 --> 00:36:47,300
this kind of unique
and unusual environment.

879
00:36:47,300 --> 00:36:49,900
So the Solar Probe Cup--

880
00:36:49,900 --> 00:36:51,400
here's a picture
of our prototype

881
00:36:51,400 --> 00:36:53,800
that we developed before
our critical design review.

882
00:36:53,800 --> 00:36:57,100
It's composed of a sensor
and then an electronics box.

883
00:36:57,100 --> 00:36:58,900
The electronics
are far enough away

884
00:36:58,900 --> 00:37:00,733
that they can hide
behind the heat shields.

885
00:37:00,733 --> 00:37:02,066
They don't get very hot.

886
00:37:02,066 --> 00:37:03,800
They're basically
at room temperature.

887
00:37:03,800 --> 00:37:07,100
The sensor itself is made
out of a whole assemblage

888

00:37:07,100 --> 00:37:09,600
of fascinating materials
that we learned about

889
00:37:09,600 --> 00:37:13,233
working with people who designed
jet-engine afterburners,

890
00:37:13,233 --> 00:37:16,066
nuclear reactor fuel rods,

891
00:37:16,066 --> 00:37:17,566
rocket nozzles.

892
00:37:17,566 --> 00:37:20,133
We use all sorts
of interesting alloys and metals

893
00:37:20,133 --> 00:37:22,200
that can operate
at very high temperature.

894
00:37:22,200 --> 00:37:24,900
We also, unfortunately,
have to be able to develop

895
00:37:24,900 --> 00:37:27,966
and sustain high voltages
within this instrument.

896
00:37:27,966 --> 00:37:29,366
Basically--
and if you're curious,

897
00:37:29,366 --> 00:37:31,400
I can tell you the details
afterwards,

898
00:37:31,400 --> 00:37:35,266
but what we do

is we use a very high voltage

899
00:37:35,266 --> 00:37:38,100
to set up
a very strong electric field,

900
00:37:38,100 --> 00:37:40,100
and then we measure the number
of particles

901
00:37:40,100 --> 00:37:43,333
that are able to make it
past that electric field.

902
00:37:43,333 --> 00:37:45,533
And then we just
raise the electric field up

903
00:37:45,533 --> 00:37:47,066
and count the number
of particles

904
00:37:47,066 --> 00:37:49,566
as a function of the strength
of the electric field.

905
00:37:49,566 --> 00:37:51,533
And that lets us take
an inventory

906
00:37:51,533 --> 00:37:54,166
of how many particles
are moving at different speeds,

907
00:37:54,166 --> 00:37:56,000
what directions
they're coming from.

908
00:37:56,000 --> 00:37:57,500
A little bit

of math and analysis,

909
00:37:57,500 --> 00:37:59,900
and you get the velocities,
density, and temperatures

910
00:37:59,900 --> 00:38:03,166
that most people
are interested in seeing.

911
00:38:03,166 --> 00:38:07,200
So, inside the instrument,
one of our favorite things

912
00:38:07,200 --> 00:38:08,433
is this is--

913
00:38:08,433 --> 00:38:11,366
this grid in the center
of Solar Probe Cup

914
00:38:11,366 --> 00:38:13,333
sits at 8 kilovolts,

915
00:38:13,333 --> 00:38:14,933
at very high voltage,

916
00:38:14,933 --> 00:38:18,933
and so it also sits
at around 1,000 degrees.

917
00:38:18,933 --> 00:38:21,000
So what we use
are tiny sapphire pins,

918
00:38:21,000 --> 00:38:22,933
synthetic sapphire crystal

919
00:38:22,933 --> 00:38:25,933

that hold that grid in place
so it can stay at 8 kilovolts

920
00:38:25,933 --> 00:38:29,266
without arcing to the rest
of the instrument.

921
00:38:29,266 --> 00:38:32,200
We use sapphire, actually,

922
00:38:32,200 --> 00:38:33,966
at a bunch of different places
within the instrument

923
00:38:33,966 --> 00:38:36,033
to isolate our sensors.

924
00:38:36,033 --> 00:38:38,000
Our sensors on this instrument
are very simple,

925
00:38:38,000 --> 00:38:39,966
just a bunch of metal plates,

926
00:38:39,966 --> 00:38:41,266
and that was important.

927
00:38:41,266 --> 00:38:43,300
If we're going to go
such a harsh environment,

928
00:38:43,300 --> 00:38:45,433
we need something that isn't
susceptible to radiation,

929
00:38:45,433 --> 00:38:46,533
that isn't gonna melt.

930
00:38:46,533 --> 00:38:48,133

And so, since all we're doing

931
00:38:48,133 --> 00:38:51,233
is counting particles
as a function of energy,

932
00:38:51,233 --> 00:38:54,900
we were just measuring current,
so we can just use metal plates.

933
00:38:54,900 --> 00:38:56,900
A lot of challenges here--

934
00:38:56,900 --> 00:38:59,500
you can't just buy coax cable
and string it up

935
00:38:59,500 --> 00:39:02,100
to this instrument
to deliver those high voltages.

936
00:39:02,100 --> 00:39:03,800
Even the cables
have temperatures running

937
00:39:03,800 --> 00:39:06,500
between 1,000 degrees
and 300 degrees.

938
00:39:06,500 --> 00:39:08,300
After we were selected,

939
00:39:08,300 --> 00:39:10,900
I visited some members
of the fusion community,

940
00:39:10,900 --> 00:39:14,400
thinking, you know,
"Okay, you know, pass on to me

941
00:39:14,400 --> 00:39:16,400
the collected knowledge
of fusion reactors

942
00:39:16,400 --> 00:39:18,066
and how to get things to run

943
00:39:18,066 --> 00:39:20,066
at these high temperatures
and voltages."

944
00:39:20,066 --> 00:39:23,200
And basically the response was,
"Wow, that sounds great.

945
00:39:23,200 --> 00:39:25,566
Let us know
what you figure out."

946
00:39:25,566 --> 00:39:28,400
So we do things that we've had
to develop ourselves,

947
00:39:28,400 --> 00:39:32,533
like we grow tubes
of sapphire crystal.

948
00:39:32,533 --> 00:39:36,533
We then encase them
in sapphire doughnuts,

949
00:39:36,533 --> 00:39:39,533
and then we laser-weld
niobium tubes around it.

950
00:39:39,533 --> 00:39:41,233
We laser-weld
'cause you can't solder

951

00:39:41,233 --> 00:39:43,566
or normally weld things
when they're gonna be heated

952
00:39:43,566 --> 00:39:44,566
to 1,000 degrees.

953
00:39:44,566 --> 00:39:46,566
The solder would just melt.

954
00:39:46,566 --> 00:39:47,800
And I'll just close

955
00:39:47,800 --> 00:39:49,733
with a little bit
about how we test these things.

956
00:39:49,733 --> 00:39:50,866
So you start out,

957
00:39:50,866 --> 00:39:53,033
you test things
in a big, fancy oven.

958
00:39:53,033 --> 00:39:55,933
That at least allows you to
answer a lot of basic questions.

959
00:39:55,933 --> 00:39:58,233
You know, will this still be
a resistor when it's that hot?

960
00:39:58,233 --> 00:39:59,833
Is it just gonna melt?

961
00:39:59,833 --> 00:40:01,566
We had a few tests
where we opened the oven,

962

00:40:01,566 --> 00:40:05,433
and we had a sad, melted pile
of instrument prototype.

963
00:40:05,433 --> 00:40:07,233
But to do realistic testing,

964
00:40:07,233 --> 00:40:09,166
we need to illuminate
this instrument

965
00:40:09,166 --> 00:40:12,033
with the actual levels
of sunlight we're gonna see

966
00:40:12,033 --> 00:40:14,033
at different distances
from the sun,

967
00:40:14,033 --> 00:40:17,500
up to nearly 500 times
the brightness at 1 au,

968
00:40:17,500 --> 00:40:18,733
or Earth's orbit.

969
00:40:18,733 --> 00:40:21,833
So one of the ways
we did this testing

970
00:40:21,833 --> 00:40:25,100
was we went to the largest
solar furnace in the world.

971
00:40:25,100 --> 00:40:27,900
This is a furnace in southern
France, in the Pyrenees.

972
00:40:27,900 --> 00:40:32,233
It can focus up to 10 megawatts

of sunlight through these doors

973
00:40:32,233 --> 00:40:35,066
into a little vacuum chamber
on the side.

974
00:40:35,066 --> 00:40:38,833
So the whole mountainside is
covered with tracking mirrors.

975
00:40:38,833 --> 00:40:40,466
This isn't
like a fisheye-lens effect.

976
00:40:40,466 --> 00:40:43,066
The whole seven-story side
of the building

977
00:40:43,066 --> 00:40:47,966
is shaped like
a big parabolic focusing lens.

978
00:40:47,966 --> 00:40:51,000
So that lets us
do our first demonstrations

979
00:40:51,000 --> 00:40:54,133
that we could come up with the
materials that could survive.

980
00:40:54,133 --> 00:40:56,933
But as my colleague
Jay Bookbinder pointed out,

981
00:40:56,933 --> 00:40:58,800
the problem
with the solar furnace

982
00:40:58,800 --> 00:41:00,800
is the sun sets at night.

983
00:41:00,800 --> 00:41:03,500
And so how are we gonna test
for a multiday encounter

984
00:41:03,500 --> 00:41:07,566
with the sun if you have to turn
things on and off every day?

985
00:41:07,566 --> 00:41:09,233
And also, what do you do
if there's a cloud

986
00:41:09,233 --> 00:41:10,400
that passes overhead?

987
00:41:10,400 --> 00:41:13,566
So, over some cocktail napkins

988
00:41:13,566 --> 00:41:16,200
at, I think, Frankfort Airport,

989
00:41:16,200 --> 00:41:17,566
we came up with this idea

990
00:41:17,566 --> 00:41:20,400
of buying used 70-millimeter
IMAX film projectors

991
00:41:20,400 --> 00:41:21,900
from movie theaters.

992
00:41:21,900 --> 00:41:24,033
They use short-arc xenon bulbs

993
00:41:24,033 --> 00:41:26,166
that have the same brightness
temperature of the sun.

994
00:41:26,166 --> 00:41:31,033
The xenon is heated
to about 6,000 degrees Kelvin.

995
00:41:31,033 --> 00:41:33,300
Instead of letting the light
diverge out

996
00:41:33,300 --> 00:41:35,366
like you're projecting
onto a movie screen,

997
00:41:35,366 --> 00:41:37,933
what we do
is we have water-cooled lenses

998
00:41:37,933 --> 00:41:40,266
that convert that light
into parallel beams.

999
00:41:40,266 --> 00:41:42,166
One projector
isn't bright enough,

1000
00:41:42,166 --> 00:41:44,300
but by using four projectors

1001
00:41:44,300 --> 00:41:46,466
and then using
some water-cooled optics,

1002
00:41:46,466 --> 00:41:48,133
we're able
to combine the light,

1003
00:41:48,133 --> 00:41:49,833
send it through
this water-cooled window

1004

00:41:49,833 --> 00:41:51,133
in this vacuum chamber,

1005
00:41:51,133 --> 00:41:55,833
and irradiate our poor
and unsuspecting instrument.

1006
00:41:55,833 --> 00:41:59,933
And so I'm just gonna end
with a final test that we did.

1007
00:41:59,933 --> 00:42:02,633
Here's our prototype
of the Cup,

1008
00:42:02,633 --> 00:42:07,566
and here's a movie of the cup
sitting at around...

1009
00:42:07,566 --> 00:42:10,566
let's see, 10 solar radii
from the sun

1010
00:42:10,566 --> 00:42:14,200
performing quite happily,
getting up to high voltage.

1011
00:42:14,200 --> 00:42:17,233
All right, so, with that,
I'm just gonna conclude

1012
00:42:17,233 --> 00:42:20,033
by saying, you know,
we're 50 years in the Space Age.

1013
00:42:20,033 --> 00:42:21,166
We still haven't figured out

1014
00:42:21,166 --> 00:42:23,000
the physics responsible

for the high temperature

1015
00:42:23,000 --> 00:42:26,266
of the solar corona
or the shape of the solar wind.

1016
00:42:26,266 --> 00:42:29,133
We need a direct measurement to
sort of answer those questions.

1017
00:42:29,133 --> 00:42:31,100
The Solar Probe is gonna give us
those measurements.

1018
00:42:31,100 --> 00:42:32,866
It's gonna transform
our knowledge

1019
00:42:32,866 --> 00:42:35,133
of the solar corona
and the solar wind.

1020
00:42:35,133 --> 00:42:39,033
Our launch is just three years
from now in the summer,

1021
00:42:39,033 --> 00:42:41,733
so please stay tuned and follow
this exciting project.

1022
00:42:41,733 --> 00:42:43,233
Thank you.

1023
00:42:43,233 --> 00:42:46,233
[applause]

1024
00:42:48,600 --> 00:42:50,566
- Thank you, Justin,
for a great talk.

1025
00:42:50,566 --> 00:42:53,100
We have time
for a few questions.

1026
00:42:53,100 --> 00:42:55,100
If you have a question,
please raise your hand,

1027
00:42:55,100 --> 00:42:57,333
and we will have a microphone
to you.

1028
00:42:57,333 --> 00:42:59,033
Okay.

1029
00:42:59,033 --> 00:43:00,966
- What are
the current best theories

1030
00:43:00,966 --> 00:43:02,833
as to where the heating
comes from in the corona?

1031
00:43:02,833 --> 00:43:04,100
- What are the current best--

1032
00:43:04,100 --> 00:43:06,166
Oh, there was a microphone.
I won't repeat.

1033
00:43:06,166 --> 00:43:08,066
So, um...

1034
00:43:08,066 --> 00:43:09,400
there are a lot of theories.

1035
00:43:09,400 --> 00:43:11,966
They tend to fall
within two camps.

1036
00:43:11,966 --> 00:43:15,100
Camp one is that you have
some kind of wave

1037
00:43:15,100 --> 00:43:18,033
that's generated
near the surface of the sun,

1038
00:43:18,033 --> 00:43:20,500
and, you know,
the entire surface of the sun

1039
00:43:20,500 --> 00:43:23,000
churns in and out on kind of
a five-minute timescale.

1040
00:43:23,000 --> 00:43:25,400
It's like a boiling pot
of water.

1041
00:43:25,400 --> 00:43:27,233
So there's a lot
of mechanical energy

1042
00:43:27,233 --> 00:43:28,833
that's being introduced there.

1043
00:43:28,833 --> 00:43:31,033
It's possible that some
of that mechanical energy

1044
00:43:31,033 --> 00:43:33,400
is able to travel up
before those waves,

1045
00:43:33,400 --> 00:43:35,066
like, damp and break,

1046

00:43:35,066 --> 00:43:37,133
and maybe they can make it
a few solar radii

1047
00:43:37,133 --> 00:43:39,733
up away from the sun
before they dissipate

1048
00:43:39,733 --> 00:43:43,033
and then locally heat the plasma
up to high temperature.

1049
00:43:43,033 --> 00:43:44,900
The other camp is,

1050
00:43:44,900 --> 00:43:47,966
you saw how there was really
hot plasma over the sunspots,

1051
00:43:47,966 --> 00:43:50,166
and I said, "Well, you can't see
magnetic field lines,

1052
00:43:50,166 --> 00:43:52,200
but they're holding
that hot plasma in place."

1053
00:43:52,200 --> 00:43:55,033
So the other idea
is maybe magnetic field

1054
00:43:55,033 --> 00:43:57,433
in the solar corona
is hitting other magnetic field,

1055
00:43:57,433 --> 00:43:59,400
explosively canceling out,

1056
00:43:59,400 --> 00:44:01,566
you know, billions of times

a second

1057
00:44:01,566 --> 00:44:03,000
distributed
all over the place,

1058
00:44:03,000 --> 00:44:05,400
and that that's heating
the atmosphere.

1059
00:44:05,400 --> 00:44:07,900
I think it's gonna be both.

1060
00:44:07,900 --> 00:44:10,333
We need to just figure out
the relative proportion

1061
00:44:10,333 --> 00:44:11,933
and relative importance
of both,

1062
00:44:11,933 --> 00:44:14,033
and it could be
that the relative importance

1063
00:44:14,033 --> 00:44:17,033
of big mechanical waves
and magnetic fields changes,

1064
00:44:17,033 --> 00:44:19,833
depending on what type
of solar wind you're in.

1065
00:44:19,833 --> 00:44:22,700
But that's why we have to make
these measurements.

1066
00:44:22,700 --> 00:44:24,733
You know, what is
the magnetic field doing?

1067
00:44:24,733 --> 00:44:25,933
Are there any waves?

1068
00:44:25,933 --> 00:44:28,066
You know, are the waves
getting any stronger?

1069
00:44:28,066 --> 00:44:29,600
You know,
when the waves go away,

1070
00:44:29,600 --> 00:44:31,000
is the plasma hotter or cooler?

1071
00:44:31,000 --> 00:44:32,333
Those are the basic questions

1072
00:44:32,333 --> 00:44:35,500
that we'll answer
to figure that out.

1073
00:44:35,500 --> 00:44:38,333
- Hi. Thank you.
Fascinating talk.

1074
00:44:38,333 --> 00:44:39,600
I had a question

1075
00:44:39,600 --> 00:44:43,566
about the high-energy
environment around the sun

1076
00:44:43,566 --> 00:44:45,933
and the associated
small wavelengths

1077
00:44:45,933 --> 00:44:49,500
associated with that energy.

1078
00:44:49,500 --> 00:44:52,133
So, in that type
of environment,

1079
00:44:52,133 --> 00:44:56,100
EMI could become a big concern,
electromagnetic interference.

1080
00:44:56,100 --> 00:45:00,066
So my question is,
how do you deal with EMI issues?

1081
00:45:00,066 --> 00:45:05,300
And also, how do you navigate
when you're operating into--

1082
00:45:05,300 --> 00:45:07,266
- Yeah, yeah,
such a crazy environment, yeah.

1083
00:45:07,266 --> 00:45:08,566
Oh, great questions.

1084
00:45:08,566 --> 00:45:10,833
So I'll answer that
in two parts.

1085
00:45:10,833 --> 00:45:12,866
One, electromagnetic
interference--

1086
00:45:12,866 --> 00:45:17,266
so the electromagnetic fields
from the sun itself

1087
00:45:17,266 --> 00:45:18,900
are not strong enough
to perturb,

1088
00:45:18,900 --> 00:45:21,233
like, the orientation
of the spacecraft,

1089
00:45:21,233 --> 00:45:25,333
but the electric field
and magnetic field instruments

1090
00:45:25,333 --> 00:45:28,566
on the spacecraft
are extremely sensitive, right?

1091
00:45:28,566 --> 00:45:31,300
Now, they don't have to be
necessarily quite as sensitive

1092
00:45:31,300 --> 00:45:33,400
as instruments, you know,
near Earth,

1093
00:45:33,400 --> 00:45:35,733
because everything's stronger
closer to the sun,

1094
00:45:35,733 --> 00:45:37,400
but we have to be
incredibly careful

1095
00:45:37,400 --> 00:45:40,100
not to generate our own noise

1096
00:45:40,100 --> 00:45:42,966
that can sort of blind
the electric field,

1097
00:45:42,966 --> 00:45:44,700
the magnetic field instruments.

1098
00:45:44,700 --> 00:45:46,633

So we're constantly doing things
with our prototypes

1099
00:45:46,633 --> 00:45:48,400
called, like, sniff tests,

1100
00:45:48,400 --> 00:45:50,733
where someone will come
with a very sensitive meter,

1101
00:45:50,733 --> 00:45:52,233
you know,
and go around our instrument

1102
00:45:52,233 --> 00:45:54,066
and look for any emission.

1103
00:45:54,066 --> 00:45:55,366
And we're very careful

1104
00:45:55,366 --> 00:45:57,933
that everything is synchronized
on the spacecraft.

1105
00:45:57,933 --> 00:46:00,066
We share one clock,
you know,

1106
00:46:00,066 --> 00:46:01,866
and all the decisions
by all the instruments

1107
00:46:01,866 --> 00:46:03,566
are made on that clock

1108
00:46:03,566 --> 00:46:05,566
so we don't, you know,
have signals

1109

00:46:05,566 --> 00:46:07,000
at very different frequencies.

1110
00:46:07,000 --> 00:46:09,400
In terms of navigation...

1111
00:46:09,400 --> 00:46:11,900
yeah, there are a lot
of challenges to this mission.

1112
00:46:11,900 --> 00:46:16,366
The photon pressure is so strong
that close to the sun

1113
00:46:16,366 --> 00:46:18,566
that left to its own devices,

1114
00:46:18,566 --> 00:46:20,733
light would flip
the spacecraft around

1115
00:46:20,733 --> 00:46:22,900
in under 30 seconds
at closest approach.

1116
00:46:22,900 --> 00:46:25,900
So we have a momentum wheel
that's constantly speeding up

1117
00:46:25,900 --> 00:46:27,266
to keep us pointed at the sun.

1118
00:46:27,266 --> 00:46:30,400
We have star trackers
to look at constellations

1119
00:46:30,400 --> 00:46:32,333
to make sure we're pointing
in the right direction.

1120
00:46:32,333 --> 00:46:33,833
There's always the risk
that one of those

1121
00:46:33,833 --> 00:46:36,533
coronal mass ejections--
that I think is great--

1122
00:46:36,533 --> 00:46:39,100
is gonna happen
when we're at closest approach.

1123
00:46:39,100 --> 00:46:42,900
In the worst case,
it could blind the star trackers

1124
00:46:42,900 --> 00:46:44,166
for a couple days.

1125
00:46:44,166 --> 00:46:48,000
So we have an inertial gyroscope
system as a backup.

1126
00:46:48,000 --> 00:46:49,466
There are three flight computers

1127
00:46:49,466 --> 00:46:52,300
that are constantly fighting
each other over who's right.

1128
00:46:52,300 --> 00:46:55,933
And the idea is the system's
designed, hopefully,

1129
00:46:55,933 --> 00:46:59,733
to be redundant enough that if
we are blinded by a solar flare,

1130
00:46:59,733 --> 00:47:02,366

we'll realize that,
we'll ignore the star trackers,

1131
00:47:02,366 --> 00:47:04,566
we'll switch
to the inertial guidance,

1132
00:47:04,566 --> 00:47:06,566
and hopefully pop out
the other side of the sun

1133
00:47:06,566 --> 00:47:07,866
in one piece.

1134
00:47:07,866 --> 00:47:09,066
It's a big challenge,

1135
00:47:09,066 --> 00:47:13,200
and anticipating the problems
is a challenge.

1136
00:47:13,200 --> 00:47:15,200
- Very nice talk, Justin.
- Oh, thank you.

1137
00:47:15,200 --> 00:47:16,900
- What you see
in the solar wind

1138
00:47:16,900 --> 00:47:19,233
is gonna depend
upon what you're flying over

1139
00:47:19,233 --> 00:47:20,366
on the surface of the sun.

1140
00:47:20,366 --> 00:47:23,466
Do these closest approaches
happen at a time

1141
00:47:23,466 --> 00:47:25,833
when you can actually observe
the surface of the sun?

1142
00:47:25,833 --> 00:47:29,800
- Yeah, so one
of our requirements

1143
00:47:29,800 --> 00:47:33,900
is that a certain number
of the encounters,

1144
00:47:33,900 --> 00:47:35,900
and in particular
the closest encounters,

1145
00:47:35,900 --> 00:47:38,866
all occur during times where,

1146
00:47:38,866 --> 00:47:40,800
you know, the region
of the sun we're flying over

1147
00:47:40,800 --> 00:47:42,333
is visible from Earth.

1148
00:47:42,333 --> 00:47:43,866
So, you know,

1149
00:47:43,866 --> 00:47:45,500
maybe we'll have
spacecraft operating,

1150
00:47:45,500 --> 00:47:46,966
you know, at other locations

1151
00:47:46,966 --> 00:47:48,500
than just Earth's orbit
around the sun,

1152
00:47:48,500 --> 00:47:50,300
but we don't want to make
that assumption.

1153
00:47:50,300 --> 00:47:52,300
So we feel like
the most likely place

1154
00:47:52,300 --> 00:47:54,166
we'll have a lot
of good solar observatories

1155
00:47:54,166 --> 00:47:58,000
in five to ten years
is gonna be Earth, yeah.

1156
00:47:58,000 --> 00:48:01,966
So the dynamics of the orbit
is very challenging.

1157
00:48:03,400 --> 00:48:05,066
- Hi.
Thanks for the talk.

1158
00:48:05,066 --> 00:48:08,366
My question was regarding
the image and animation

1159
00:48:08,366 --> 00:48:10,066
you showed of the--

1160
00:48:10,066 --> 00:48:11,233
It was a false-color sun,

1161
00:48:11,233 --> 00:48:13,100
and it showed
the coronal mass ejection.

1162

00:48:13,100 --> 00:48:15,266
I was wondering
when you take that image,

1163
00:48:15,266 --> 00:48:17,366
and if you process it
quickly enough, I guess,

1164
00:48:17,366 --> 00:48:20,000
that's the time that the photons
arrive at Earth.

1165
00:48:20,000 --> 00:48:22,400
And I was curious if you
can use that as prediction

1166
00:48:22,400 --> 00:48:24,366
and if the charged particles

1167
00:48:24,366 --> 00:48:28,233
that disrupt our atmosphere
can be predictive.

1168
00:48:28,233 --> 00:48:31,166
Like, how long does that take
to arrive after that?

1169
00:48:31,166 --> 00:48:32,566
- Excellent, excellent.

1170
00:48:32,566 --> 00:48:36,100
So light from the surface
of the sun

1171
00:48:36,100 --> 00:48:38,066
takes 8 1/2 minutes
to reach us.

1172
00:48:38,066 --> 00:48:41,100
Unfortunately,

the most energetic radiation

1173
00:48:41,100 --> 00:48:43,133
is traveling
at nearly the speed of light,

1174
00:48:43,133 --> 00:48:46,400
so, you know,
the photons get here,

1175
00:48:46,400 --> 00:48:51,933
like, 0.001% faster than
the high-energy particles.

1176
00:48:51,933 --> 00:48:54,866
The shockwave,
that big eruption itself,

1177
00:48:54,866 --> 00:48:57,800
can take two to three days
to get here.

1178
00:48:57,800 --> 00:49:00,233
I mean, there are
some very famous events.

1179
00:49:00,233 --> 00:49:02,566
There was a great one
in the 19th century

1180
00:49:02,566 --> 00:49:07,100
that shut down worldwide
telegraph lines for two days

1181
00:49:07,100 --> 00:49:09,166
once the coronal mass ejection
reached Earth.

1182
00:49:09,166 --> 00:49:10,900
That one took, like,

20 hours to get to us.

1183
00:49:10,900 --> 00:49:12,933
It was moving very fast.

1184
00:49:12,933 --> 00:49:15,866
So, if you see the flare

1185
00:49:15,866 --> 00:49:18,000
and you're worried
about the coronal mass ejection,

1186
00:49:18,000 --> 00:49:21,066
you have half a day,
a day advance warning.

1187
00:49:21,066 --> 00:49:24,233
So those images
from Solar Dynamics Observatory,

1188
00:49:24,233 --> 00:49:25,933
the images are recorded.

1189
00:49:25,933 --> 00:49:28,100
They're sent
to a dedicated receiver

1190
00:49:28,100 --> 00:49:29,866
in White Sands, New Mexico.

1191
00:49:29,866 --> 00:49:32,366
They're distributed
to the East and West Coast,

1192
00:49:32,366 --> 00:49:34,933
and they're distributed with
a latency of under a minute,

1193
00:49:34,933 --> 00:49:37,500

and NOAA makes use
of those images,

1194
00:49:37,500 --> 00:49:39,733
constantly looking
for an eruption

1195
00:49:39,733 --> 00:49:41,333
that's about to occur.

1196
00:49:41,333 --> 00:49:44,133
What we'd really like to be able
to do, though, is, you know--

1197
00:49:44,133 --> 00:49:47,400
I hope we're going to get
into the business

1198
00:49:47,400 --> 00:49:49,800
of sending humans
into deep space,

1199
00:49:49,800 --> 00:49:52,866
and even if we're trying
to get back to the moon,

1200
00:49:52,866 --> 00:49:55,400
we need the ability to predict
one of these events,

1201
00:49:55,400 --> 00:49:57,400
you know, more than
a few minutes in advance.

1202
00:49:57,400 --> 00:49:59,066
You know,
we want to be able to say,

1203
00:49:59,066 --> 00:50:00,866
"What's the outlook

over the next two weeks?"

1204
00:50:00,866 --> 00:50:02,066
If we want to go to Mars,

1205
00:50:02,066 --> 00:50:03,566
ideally we'd like
to be able to say,

1206
00:50:03,566 --> 00:50:06,133
"What's the outlook
over the next six months?"

1207
00:50:06,133 --> 00:50:08,566
I don't know
if that's ever gonna happen,

1208
00:50:08,566 --> 00:50:11,100
but we really need to expand

1209
00:50:11,100 --> 00:50:15,533
the lead time that we
can predict these events.

1210
00:50:15,533 --> 00:50:16,633
- I had a question

1211
00:50:16,633 --> 00:50:18,400
about the shockwaves
that are released

1212
00:50:18,400 --> 00:50:21,033
as the coronal mass ejections
are emitted.

1213
00:50:21,033 --> 00:50:25,066
So a shockwave
is a concentration of pressure

1214

00:50:25,066 --> 00:50:29,733
which seems to have
similarities to sound,

1215
00:50:29,733 --> 00:50:32,266
because sound travels
as a compression wave.

1216
00:50:32,266 --> 00:50:36,066
So I wonder, is it possible
during this mission

1217
00:50:36,066 --> 00:50:39,066
to actually hear the sun

1218
00:50:39,066 --> 00:50:41,400
because of the pressure waves
that are coming off of it?

1219
00:50:41,400 --> 00:50:45,000
- Yeah, so now we're getting
to my bread and butter.

1220
00:50:45,000 --> 00:50:47,433
Yeah, so that's one
of the things that we do

1221
00:50:47,433 --> 00:50:50,133
as a very powerful test
of these different theories,

1222
00:50:50,133 --> 00:50:51,733
is we can actually watch

1223
00:50:51,733 --> 00:50:53,233
all these different kinds
of waves

1224
00:50:53,233 --> 00:50:54,933
going past the spacecraft,

1225
00:50:54,933 --> 00:50:57,400
and so locally
we can see, you know,

1226
00:50:57,400 --> 00:51:00,133
how much magnetic waves,
how much sound waves.

1227
00:51:00,133 --> 00:51:02,533
You know, that relative mix
tells you important things.

1228
00:51:02,533 --> 00:51:04,000
But, actually,

1229
00:51:04,000 --> 00:51:06,366
you hit on something really cool
the spacecraft will do.

1230
00:51:06,366 --> 00:51:09,533
The shockwaves, sometimes
when they're strong enough,

1231
00:51:09,533 --> 00:51:12,133
they actually generate
radio waves,

1232
00:51:12,133 --> 00:51:13,400
and the radio waves

1233
00:51:13,400 --> 00:51:15,366
come out at a frequency

1234
00:51:15,366 --> 00:51:16,866
that's only a function

1235
00:51:16,866 --> 00:51:19,033
of the density of the plasma

at the shockwave.

1236
00:51:19,033 --> 00:51:23,466
So we have big antennas on board
that can detect the radio waves.

1237
00:51:23,466 --> 00:51:25,000
It's really,

1238
00:51:25,000 --> 00:51:27,566
you know, at and below,
like, tens of megahertz,

1239
00:51:27,566 --> 00:51:31,233
but one way people search
for when those waves occur

1240
00:51:31,233 --> 00:51:33,966
is they actually
speed up the sound

1241
00:51:33,966 --> 00:51:36,866
and turn it
into an audible recording

1242
00:51:36,866 --> 00:51:38,166
and listen to it.

1243
00:51:38,166 --> 00:51:40,233
But, yeah, so we should be able
to hear those shockwaves

1244
00:51:40,233 --> 00:51:42,566
from the radio emission.

1245
00:51:44,066 --> 00:51:45,566
- You mentioned that sunspots

1246
00:51:45,566 --> 00:51:48,933

were much cooler than
the surface of the sun normally.

1247
00:51:48,933 --> 00:51:52,900
Is the actual atmospheric
environment hostile enough

1248
00:51:52,900 --> 00:51:55,566
that we'll never
be able to take advantage

1249
00:51:55,566 --> 00:51:57,066
of that with a probe?

1250
00:51:57,066 --> 00:51:59,166
Can we ever get close enough
to make use of that?

1251
00:51:59,166 --> 00:52:02,200
- Oh, I like that.

1252
00:52:02,200 --> 00:52:05,400
So...
[sighs]

1253
00:52:05,400 --> 00:52:07,233
No, one of the challenges
is just the mere act

1254
00:52:07,233 --> 00:52:09,066
of getting there.

1255
00:52:09,066 --> 00:52:13,433
So you might be able to hover
or pass over a darker region

1256
00:52:13,433 --> 00:52:15,433
that's maybe
1,000 degrees cooler,

1257
00:52:15,433 --> 00:52:16,566
but on your way there,

1258
00:52:16,566 --> 00:52:18,400
you're gonna see
the whole solar disc,

1259
00:52:18,400 --> 00:52:21,366
so there'd be a lot of energy
to be absorbing,

1260
00:52:21,366 --> 00:52:25,400
and then it would be less bad
than it would be otherwise

1261
00:52:25,400 --> 00:52:26,900
over the sunspot.

1262
00:52:26,900 --> 00:52:29,900
Of course, one other issue
with a sunspot is it's cooler

1263
00:52:29,900 --> 00:52:32,400
because it has
a magnetic field

1264
00:52:32,400 --> 00:52:33,900
that's, like,
1,000 times stronger

1265
00:52:33,900 --> 00:52:36,000
than Earth's magnetic field,

1266
00:52:36,000 --> 00:52:37,900
so you'd have to make sure
your electronics

1267
00:52:37,900 --> 00:52:41,033
didn't react adversely,

but I like where you're going.

1268
00:52:41,033 --> 00:52:44,566
I think we need
a solar skimmer,

1269
00:52:44,566 --> 00:52:46,633
a solar surfer.

1270
00:52:46,633 --> 00:52:48,200
- And so...

1271
00:52:48,200 --> 00:52:50,733
please join me
in thanking Dr. Kasper

1272
00:52:50,733 --> 00:52:52,566
for an excellent seminar.

1273
00:52:52,566 --> 00:52:55,566
[applause]