The Millimeter View of Stellar Flares

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The Team

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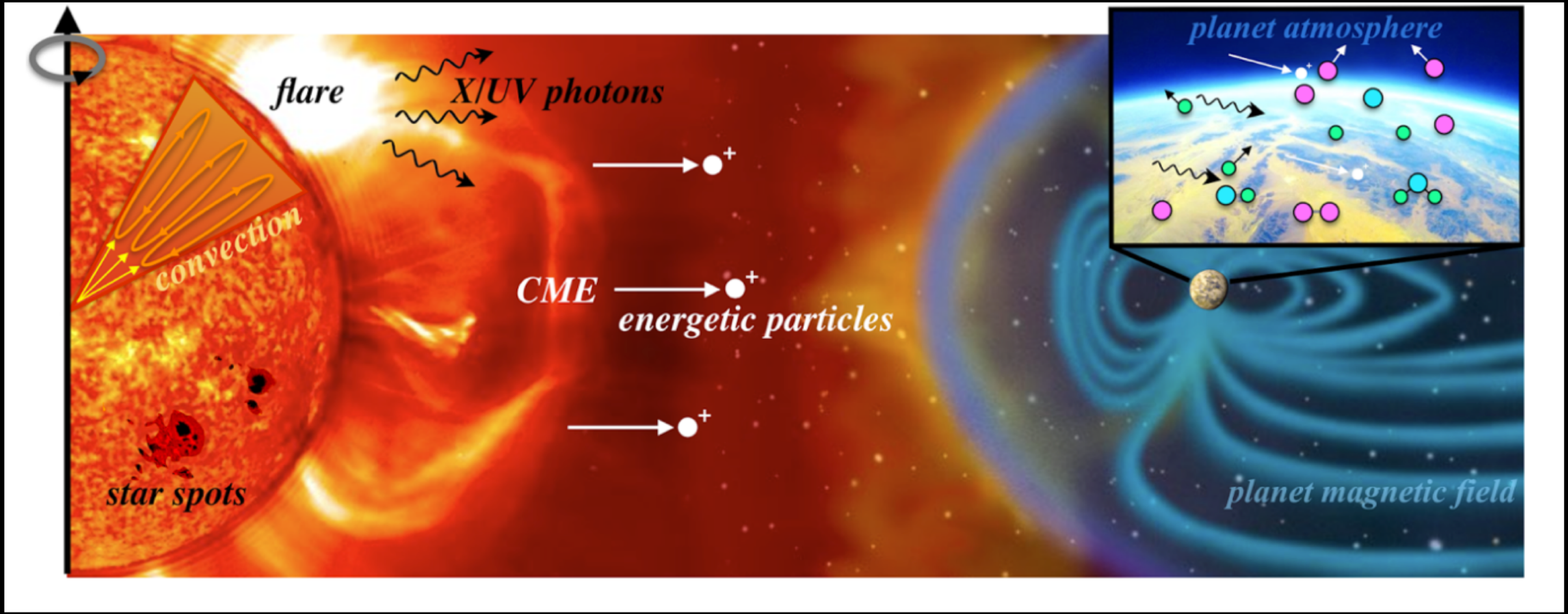
Stars are active (even our Sun!)

Large flares can modify, ionize, and erode a planet's atmosphere over time including the photodissociation of molecules such as water and ozone



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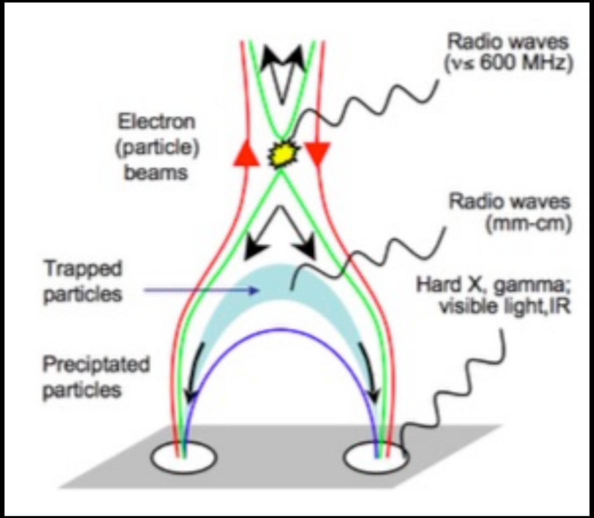
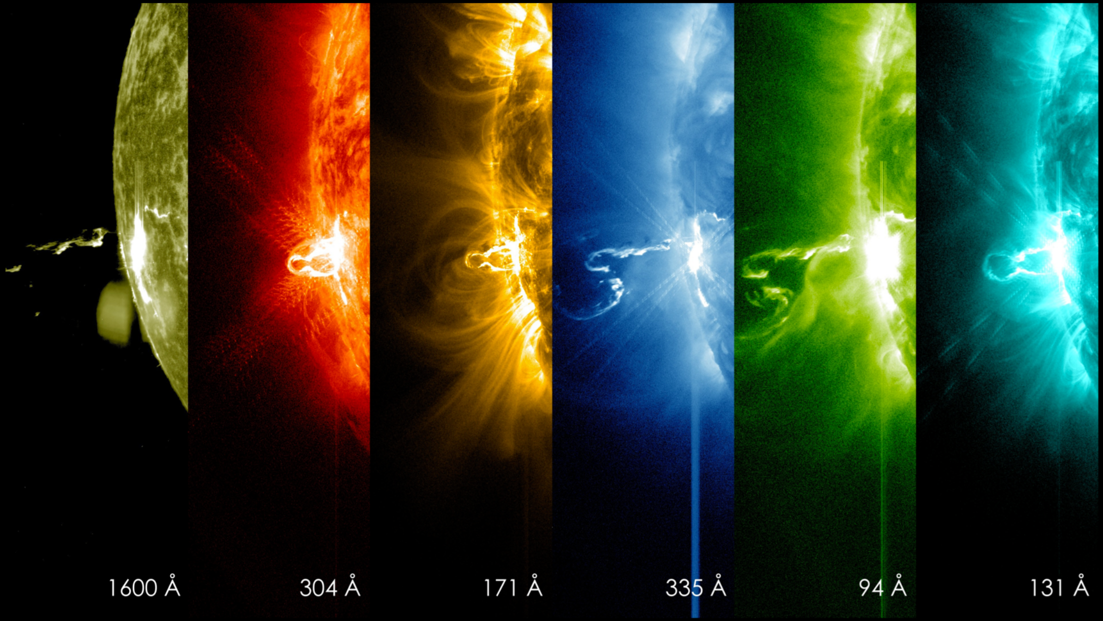
Stars flare across the entire electromagnetic spectrum

No single observation (at any wavelength) can give us a complete picture of the physics at work or the energies produced during a stellar flare

Goal: Use multiwavelength observations to inform planetary atmospheric models





Credit: Klein & Dalla (2017)

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Proxima Cen hosts the closest potentially habitable planet

The Star

spectral type = M5.5V

distance = 1.3 pc

Dust Rings?

(1) warm dust at ~0.4 AU

(2) a cold belt from 1– 4 AU

(3) an outer belt at ~30 AU

The Planet(s)

$m_p \sin i$ = 1.3 $M_\oplus$

a = 0.05 AU

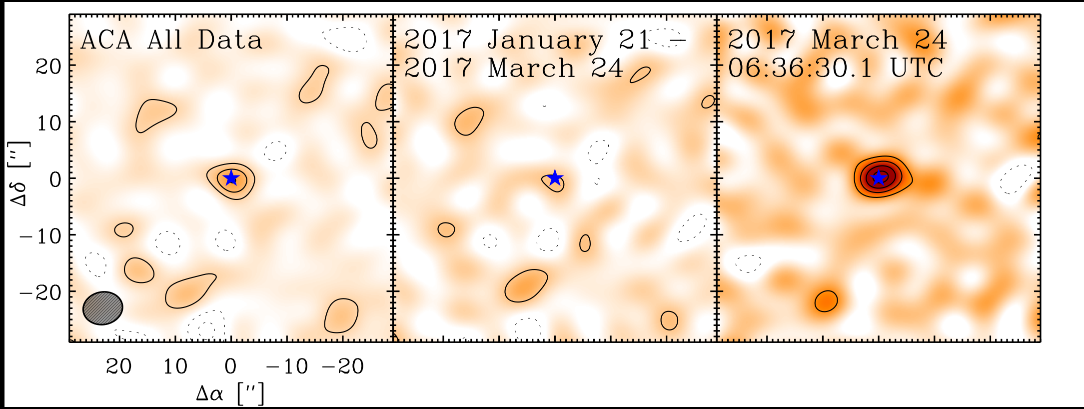
$m_p \sin i$ = 5.8 $M_\oplus$

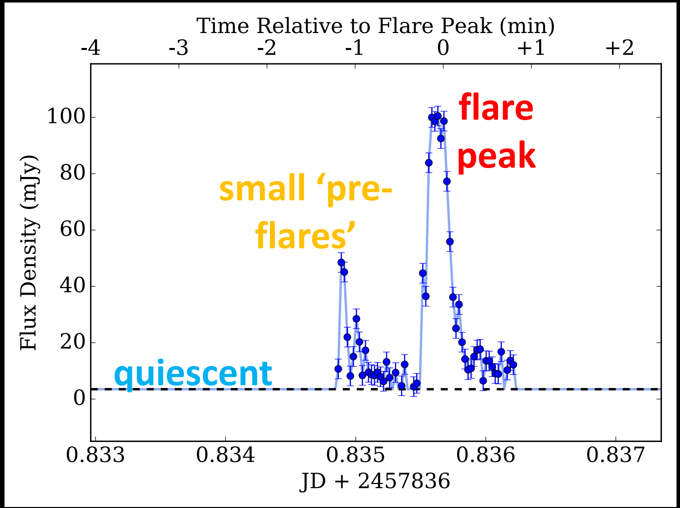
a = 1.5 AU

Credit: Anglada-Escude+ (2016), Anglada+ (2017), Damasso+ (2020)

Previous claims of dust rings from ALMA turned out to be a flare

All Obs. Obs. 1 – 12 Obs. 13





Flux = 340 ± 60 μJy

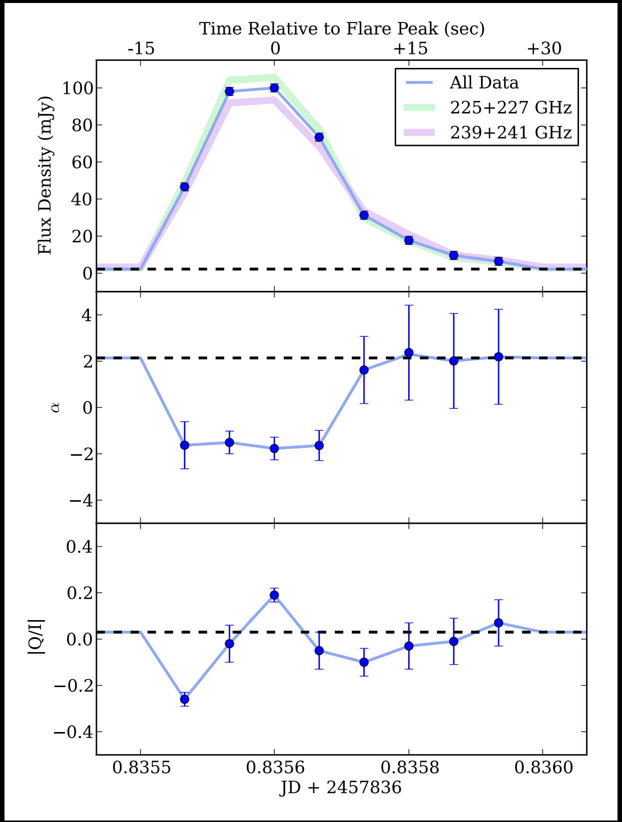
Flux <200 μJy (3σ upper limit)

Flux = 1.17 ± 0.1 mJy

No disks, but the first detection of millimeter flaring emission from a M dwarf!

Credit: MacGregor+ (2018)

This opened a new observational window on stellar flaring



Properties of Proxima Cen flare:

1000× brighter at flare peak

10x brighter at peak than brightest solar flares at millimeter wavelengths

Falling spectral index with frequency and evidence for linear polarization

Credit: MacGregor+ (2018)

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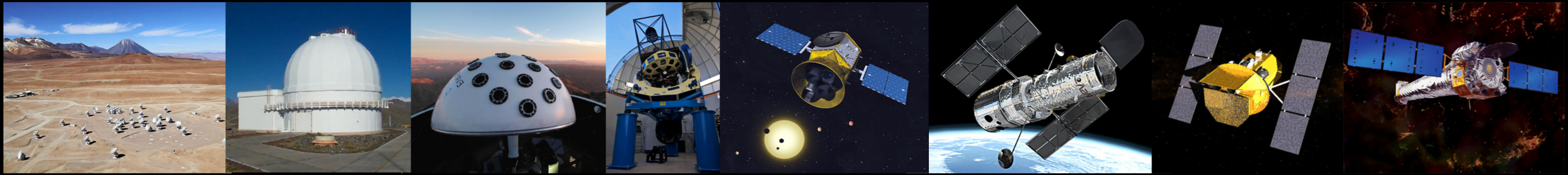
We need longer observing campaigns…

…to understand the physics of stellar flaring at millimeter wavelengths and its potential impact on the habitability of exoplanets



ALMA
millimeter

duPont
optical spectroscopy

Evryscope
optical photometry

LCOGT 1-m
optical photometry

TESS
optical (space)

HST
UV (space)

Swift
UV, X-ray (space)

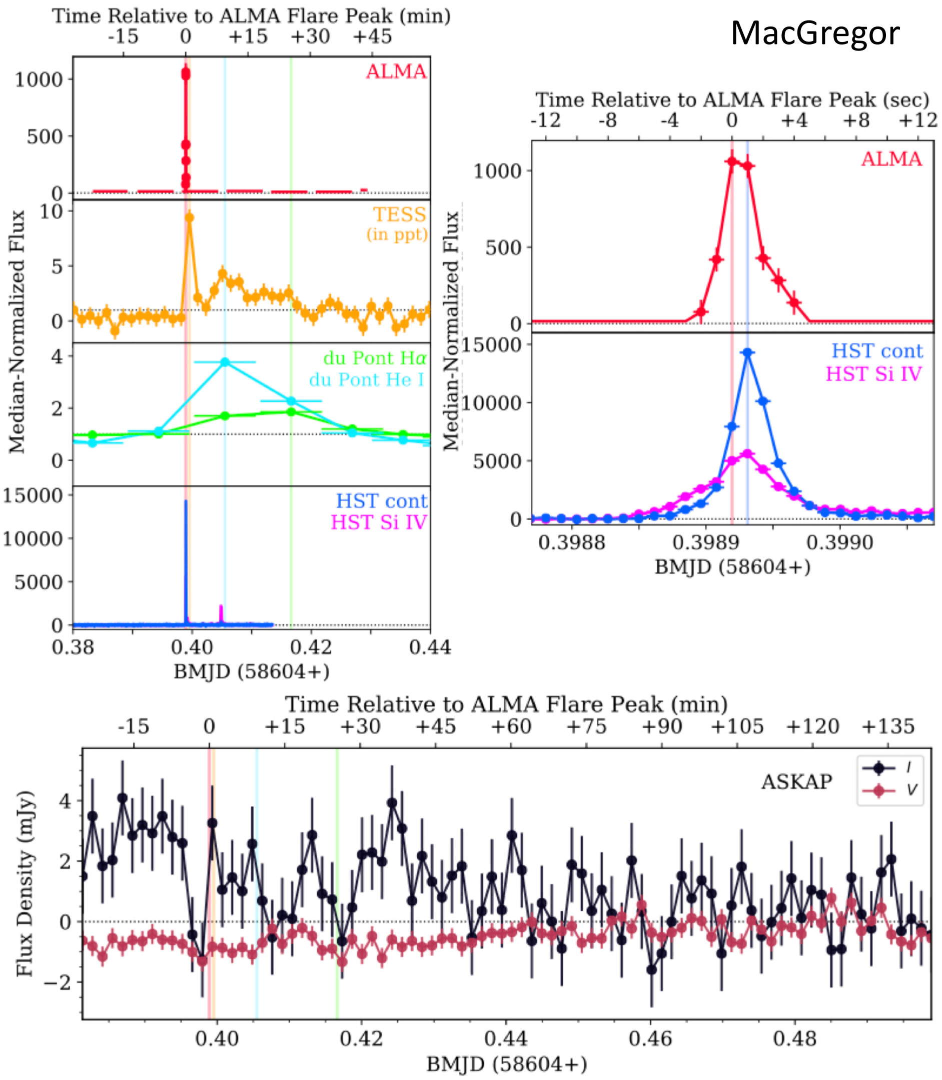
Chandra
X-ray (space)

Observed Proxima Centauri simultaneously for 40 hours between April—July 2019 using a broad range of ground- and space-based facilities

We have detected the largest flare to date with HST and ALMA on 2019 May 1

Millimeter and UV emission trace each other closely, while optical emission appears delayed

Could millimeter observations be a useful tracer of the high energy radiation environment of exoplanets?



Credit: MacGregor+ (2021)

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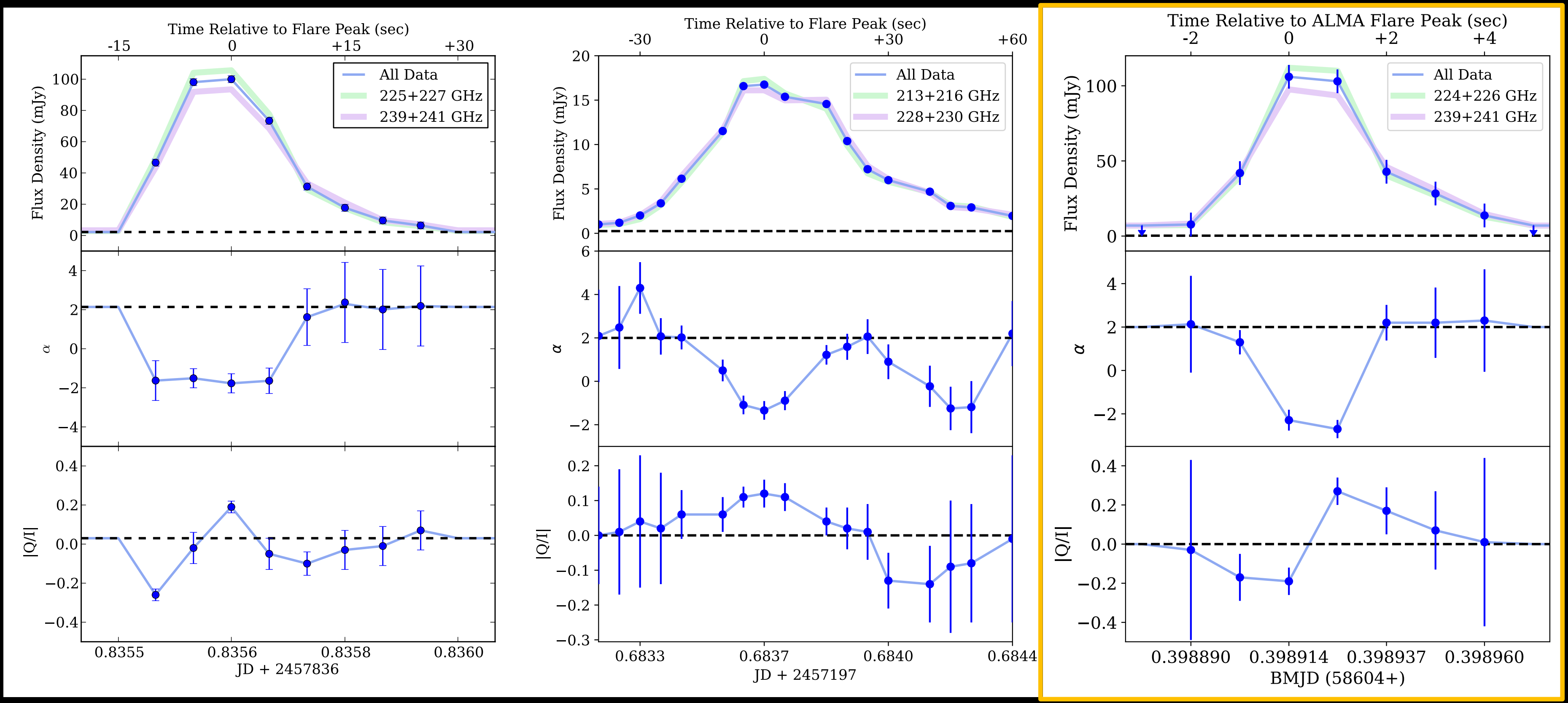
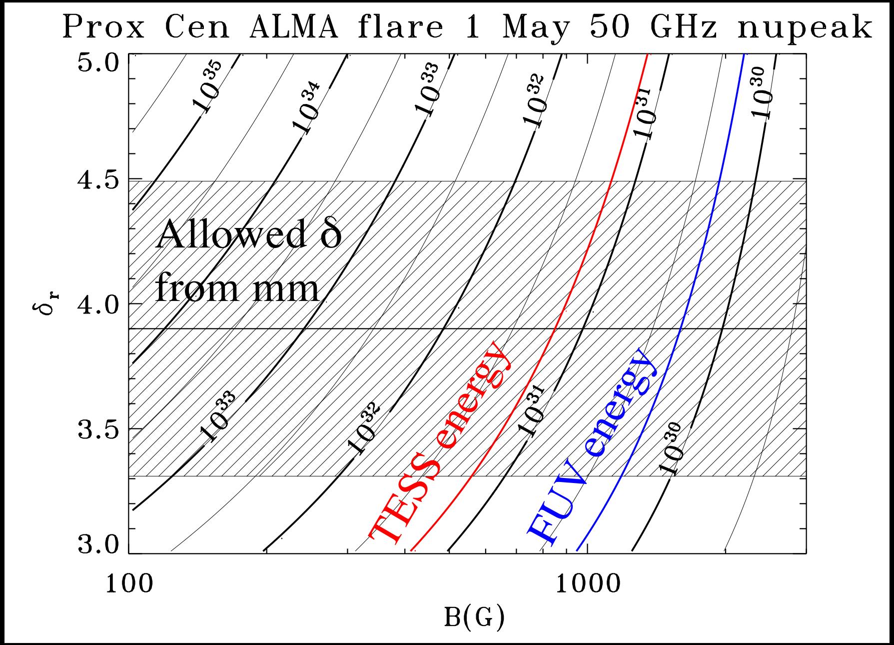
This flare shows similar properties to previous millimeter flares



Credit: MacGregor+ (2018), MacGregor+ (2020), MacGregor+ (2021)

We can constrain the associated magnetic field strength



Assuming optically thin gyrosynchrotron emission

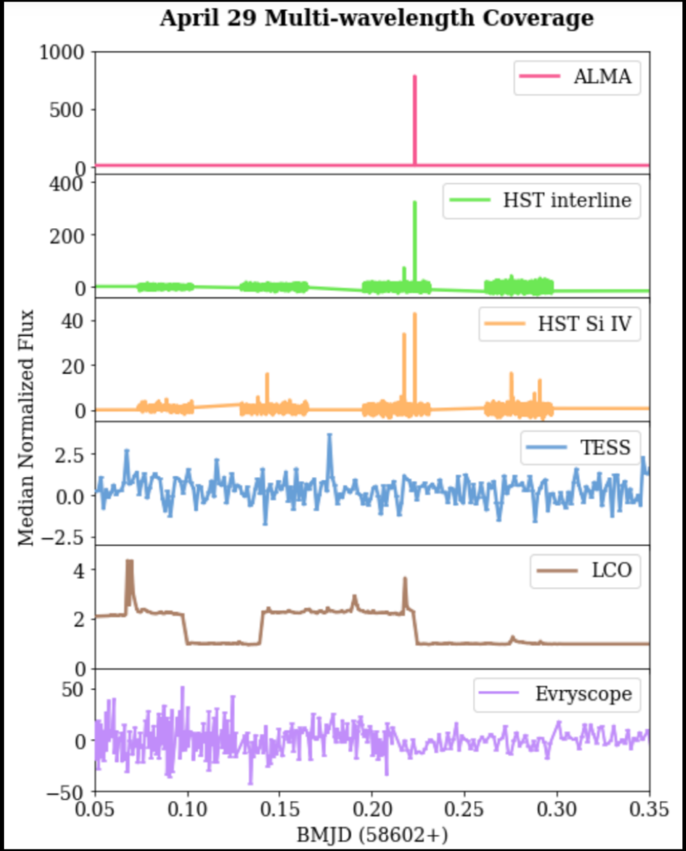
We can infer the power-law index of non-thermal electrons from the millimeter spectral index:

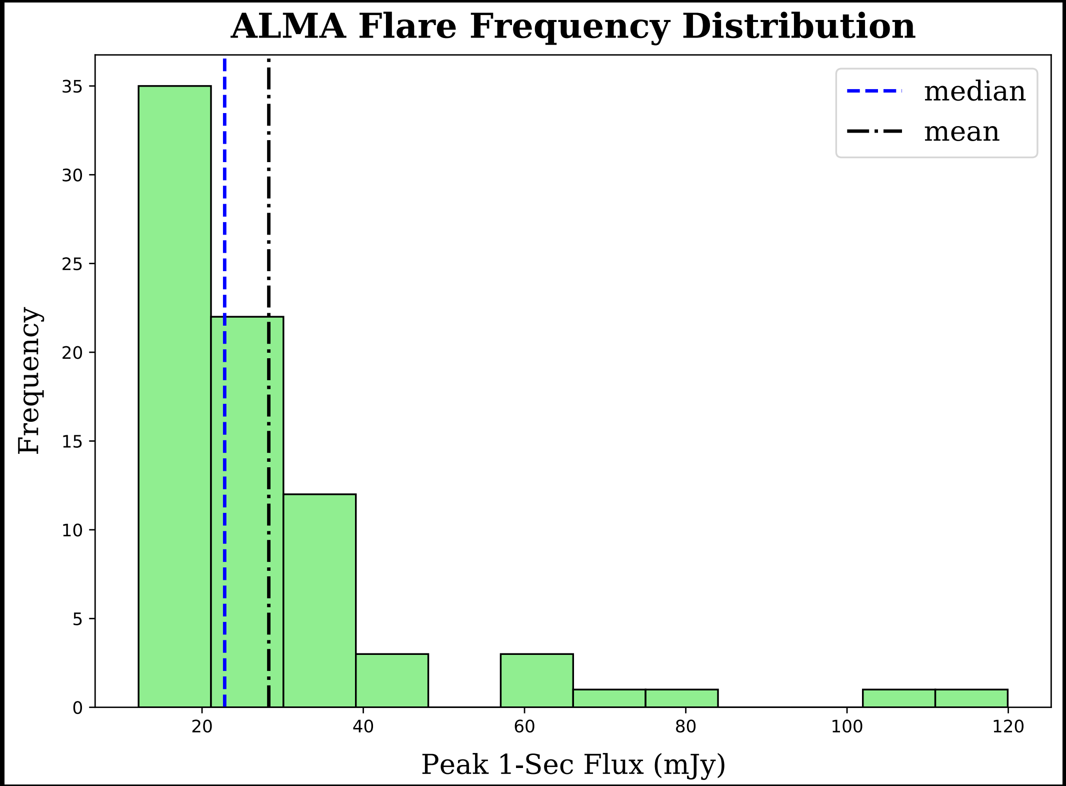
$$\alpha = 1.22 - 0.9\delta_r$$

Implies a magnetic field strength between 400-1500 G

Credit: MacGregor+ (2021), Osten+ (2016)

We are now getting the first statistics on millimeter flare rates





Credit: MacGregor, Estes+ (in prep.)

Anna Estes

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Sun-like stars flare at millimeter wavelengths, too!

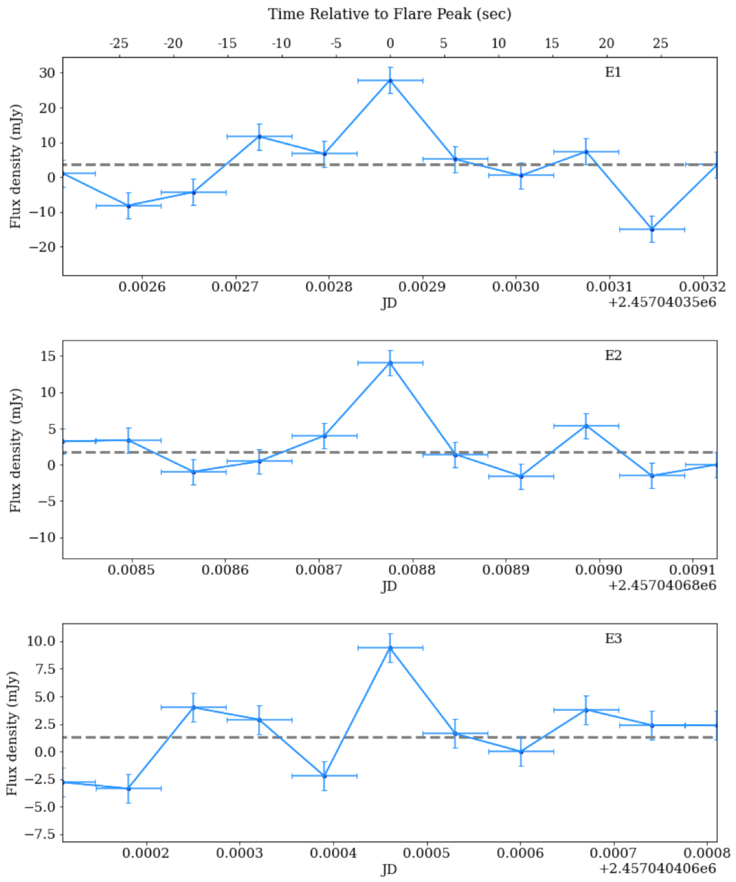

Table 1. Millimeter Properties for All Detected Flares

Star	Flare†	Peak Flux Density (mJy)	Peak L_R 10^{13}erg s^{-1} Hz^{-1}	$t_{1/2}$ (sec)	α	$\|Q/I\|$
AU Mic	A1	15	196	35	-1.30 ±0.05	>0.12±0.04
	A2	5	69	9	‡	‡
Proxima Cent	P1	45	9.2	4	‡	‡
	P2	20	4.1	2.8	‡	‡
	P3	10	2.0	2.4	‡	‡
	P4	100	20	16.4	-1.77 ± 0.45	>0.19 ±0.02
	P5	106	21	2.8	-2.29 ± 0.48	>-0.19 ±0.07
ϵ Eridani	E1	28	34	7.9	1.81 ± 1.94	>0.08±0.12
	E2	14	17	9.0	7.29 ± 2.89	>-0.48 ± 0.15
	E3	9	11	6.6	-2.83 ±2.33	>-0.11±0.19

Three flares detected from Epsilon Eridani in archival ALMA data

Credit: Burton+ (in prep.)

Kiana Burton

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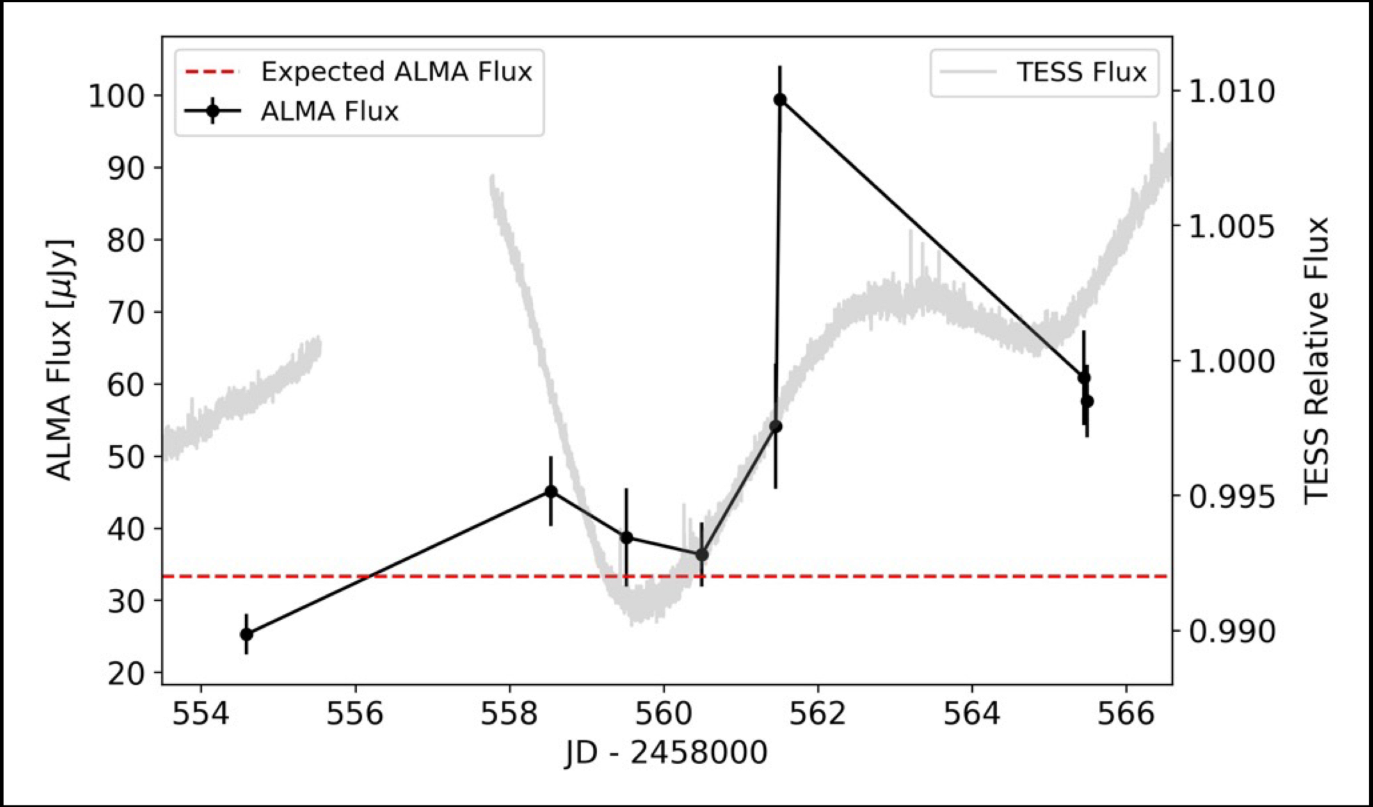
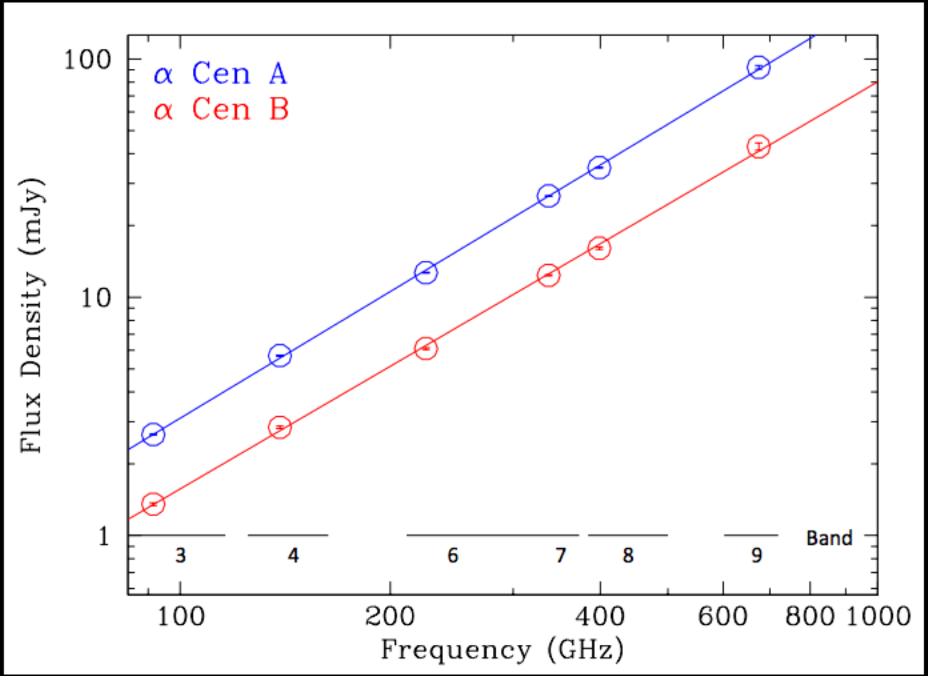


Credit: MacGregor, Stark, Hurt+ (in prep.)

Non-Flaring Emission

Observations of Sun-like stars (Alpha Cen A/B, Epsilon Eridani) show increasing brightness temperature at longer wavelengths

Chromosphere becomes optically thick at longer wavelengths, and observations probe higher (hotter) regions in the stellar atmosphere



Credit: Liseau (2019), MacGregor+ (2016)

What Could CMB-S4 Contribute?

Statistics – So far, we only have a millimeter FFD for one star (Proxima Centauri). We need to study many more stars to better understand the properties and emission mechanisms of millimeter stellar flaring. Are there differences between stars with different spectral types, ages, etc.?

Characterization – Multi-band observations can constrain the spectral index and magnetic field strength. If millimeter and UV emission are correlated, we could place some constraints on UV emission. Taking this analysis a step further, we can start to consider the surrounding environment of planet-hosting stars.

All-Sky Mapping – What is the distribution of these flaring stars across the sky?

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