An Overview of Stellar Radio Astronomy

Jeffrey Linsky

JILA/University of Colorado

Boulder Colorado USA

Radio Stars: from kHz to THz

MIT Haystack Observatory

November 1, 2017

Outline

- Perspective
- Thermal emission sources – neutral gas, dust, free-free, gyroresonance, winds
- Non-thermal emission sources – gyrosynchrotron, synchrotron, electron-cyclotron maser instability, plasma
- Insights from high-resolution interferometry
- Some major opportunities that stellar radio observations can now address
- Conclusions – what I look forward to learning at this conference

From Karen O’Neil – Director of the Green Bank Observatory

On October 17, 1957, the National Radio Astronomy Observatory came into existence. Over the past 60 years, the scientific discoveries and milestones achieved at the site have been momentous. The list of accomplishments is far too large to fit within one article, but they include: the first search for extraterrestrial intelligence; creation of the Drake equation; discovery of flat galactic rotation curves; first pulsar discovered in a supernova remnant; first organic polyatomic molecule detected in interstellar space; black hole detected at the center of the Milky Way; determination of the Tully-Fisher relationship; detection of the first interstellar anion; measurement of the most massive neutron star known; first high angular resolution image of the Sunyaev-ZelâDovich Effect; discovery of only known millisecond pulsar in a stellar triple system; discovery of pebble-sized proto-planets in Orion, and the first detection of a chiral molecule in space.

Perspective

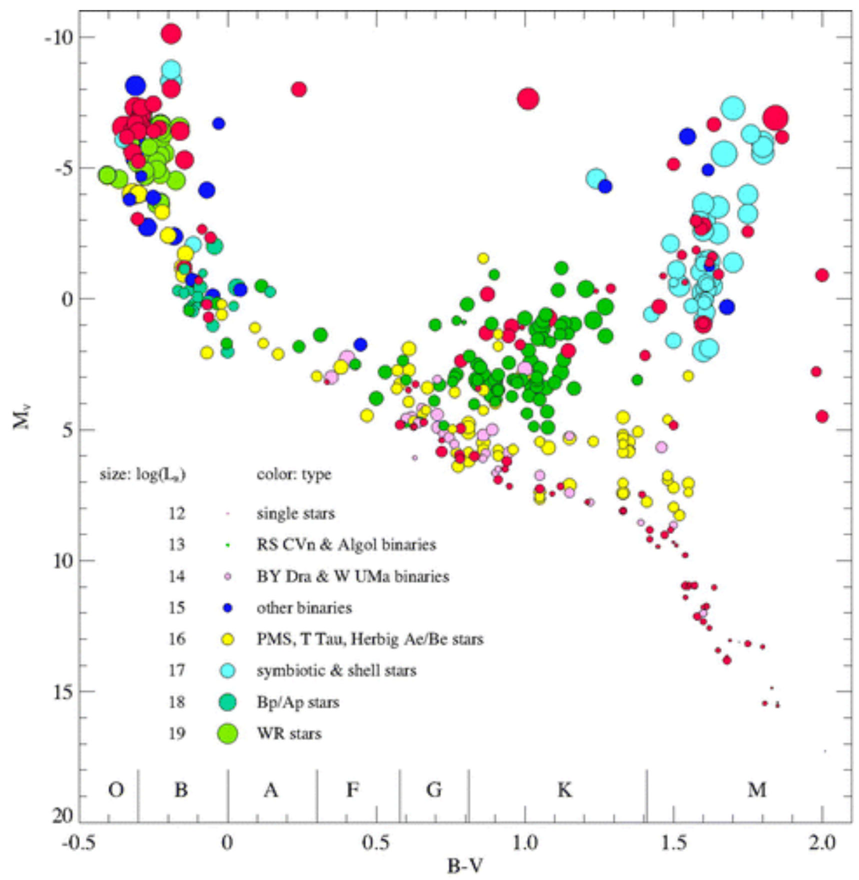
- Radio observations of stars provide unique information that cannot be obtained from observations at other wavelengths
- ALMA, JVLA, and SKA will provide greatly enhanced capabilities in sensitivity, spectral range, time resolution, multi-wavelength, etc.
- We need to look beyond individual targets and specific phenomena to general principles and detailed models that have predictive capability for radio and other wavelengths.
- This workshop should identify the important problems that radio observations can address and suggest feasible road maps for solving these problems.

Some major opportunities in astrophysics that stellar radio observations can now address

- What are the physical processes by which host stars control the evolution and habitability of their exoplanets?
- How do young stars and their planets form and evolve in their common disk environment?
- How is stellar magnetic field energy converted into heat, high energy particles, and mass loss?
- What physical processes control mass loss from stars across the H-R diagram and the effects of mass loss on stellar evolution?

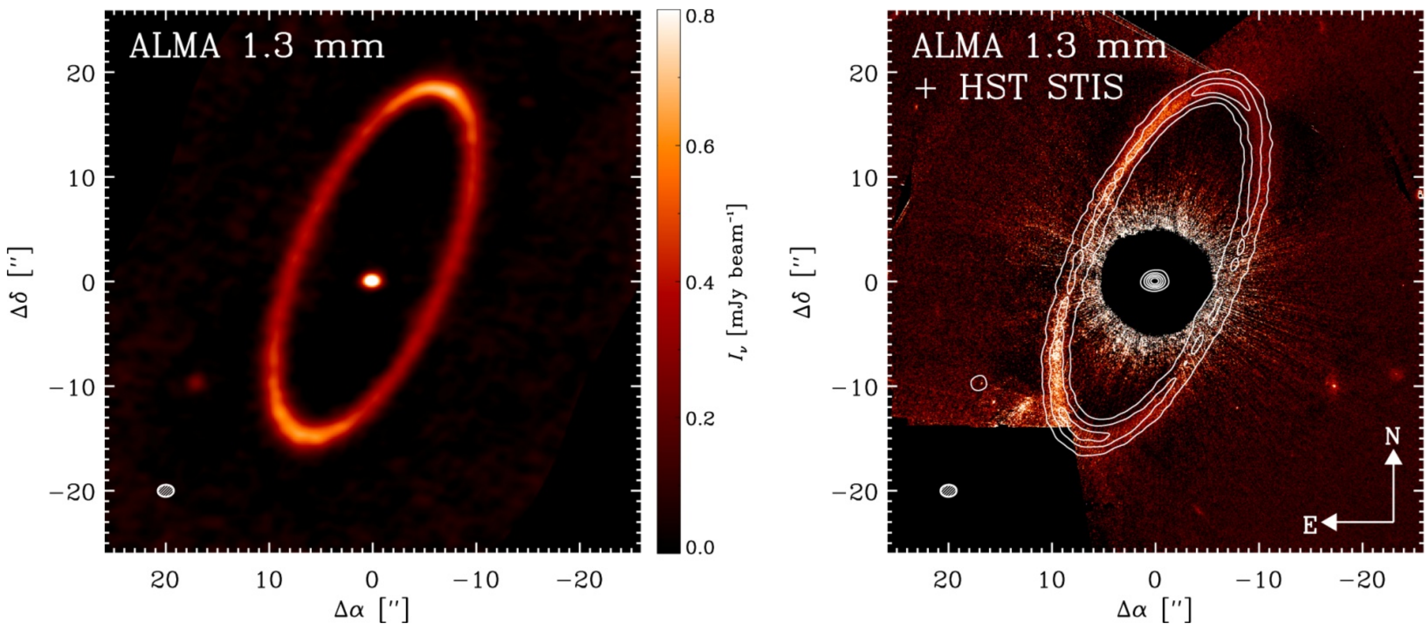
An H-R diagram of stars detected at radio wavelengths (Güdel ARAA 40, 217 (2002))

- Radio emission is detected from almost all stellar types O to M), brown dwarfs (L and T), and planets (Jupiter, Saturn).
- Also pre-main sequence stars, evolved giants and supergiants and spectroscopic binaries.
- A diversity of radio emission mechanisms. Very rich phenomenology.
- Many more detections since 2002.



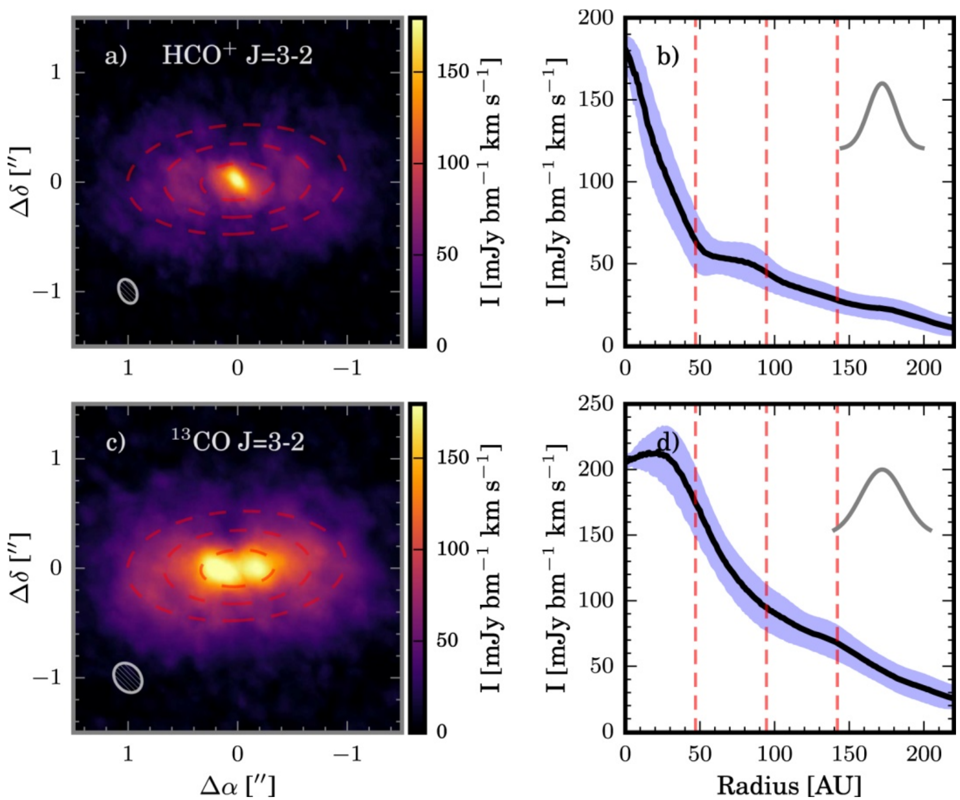
Thermal emission from dust and neutral gas in protoplanetary disks and circumstellar envelopes

Millimeter map of the outer debris disk of Formalhaut (MacGregor ApJ 842, 8 (2017))



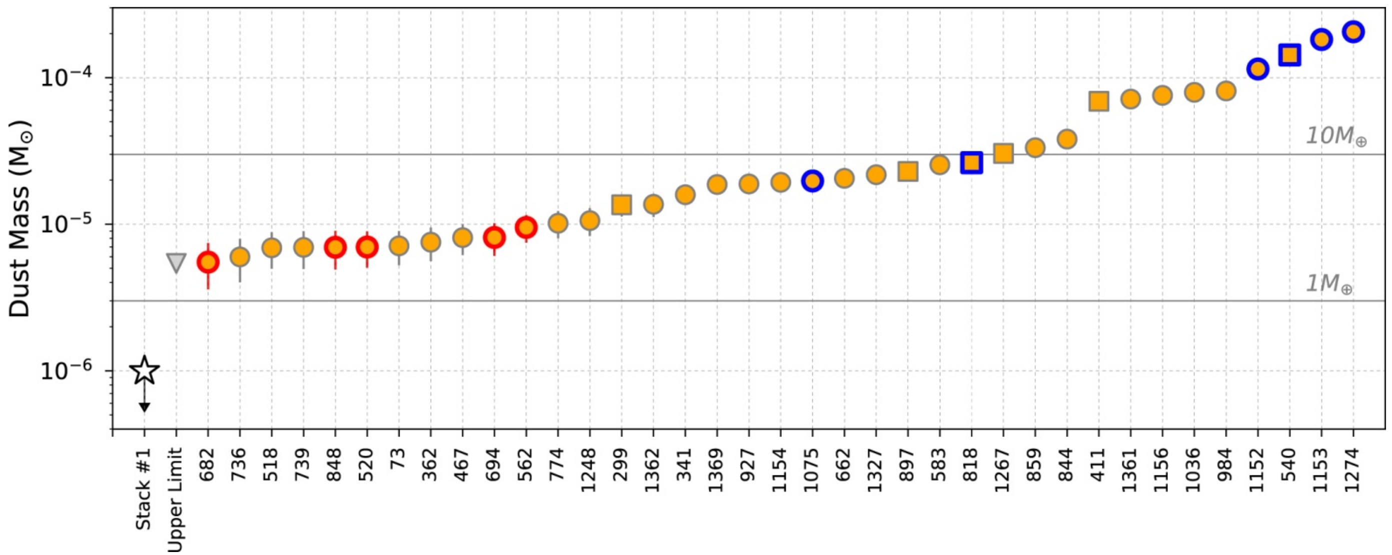
* 1.3 continuum emission from mm size dust that not perturbed by radiation.
* Shape and size of the ring result from planetary interactions.
* Comparison with scattered light from small grains (HST/STIS (coronograph).
* Beam size 1.6x1.1 arcsec (12x9 AU). Disk width probably resolved.
* Formalhaut b may be a dust cloud rather than an exoplanet.
* Star fainter at 1.3 mm that predicted by photospheric models. Why?

ALMA observations of the protoplanetary disk of AA Tau (Loomis et al. ApJ 840, 23 (2017))



- 1.3 mm continuum image shows 3 dust rings (vertical red dashed lines).
- Are gaps between rings produced by exoplanets?
- HCO^+ and ^{13}CO show emission from gas close to star but not in rings.
- What is the spatial relation of dust and gas (perhaps gap crossing accretion)?
- Baseline for these data only 1-2 km and only bands 6 and 7.
- This is only the beginning of what can be observed by ALMA.

ALMA survey of protoplanetary disks in the σ Orionis cluster (Ansdell et al. AJ 153, 240 (2017))

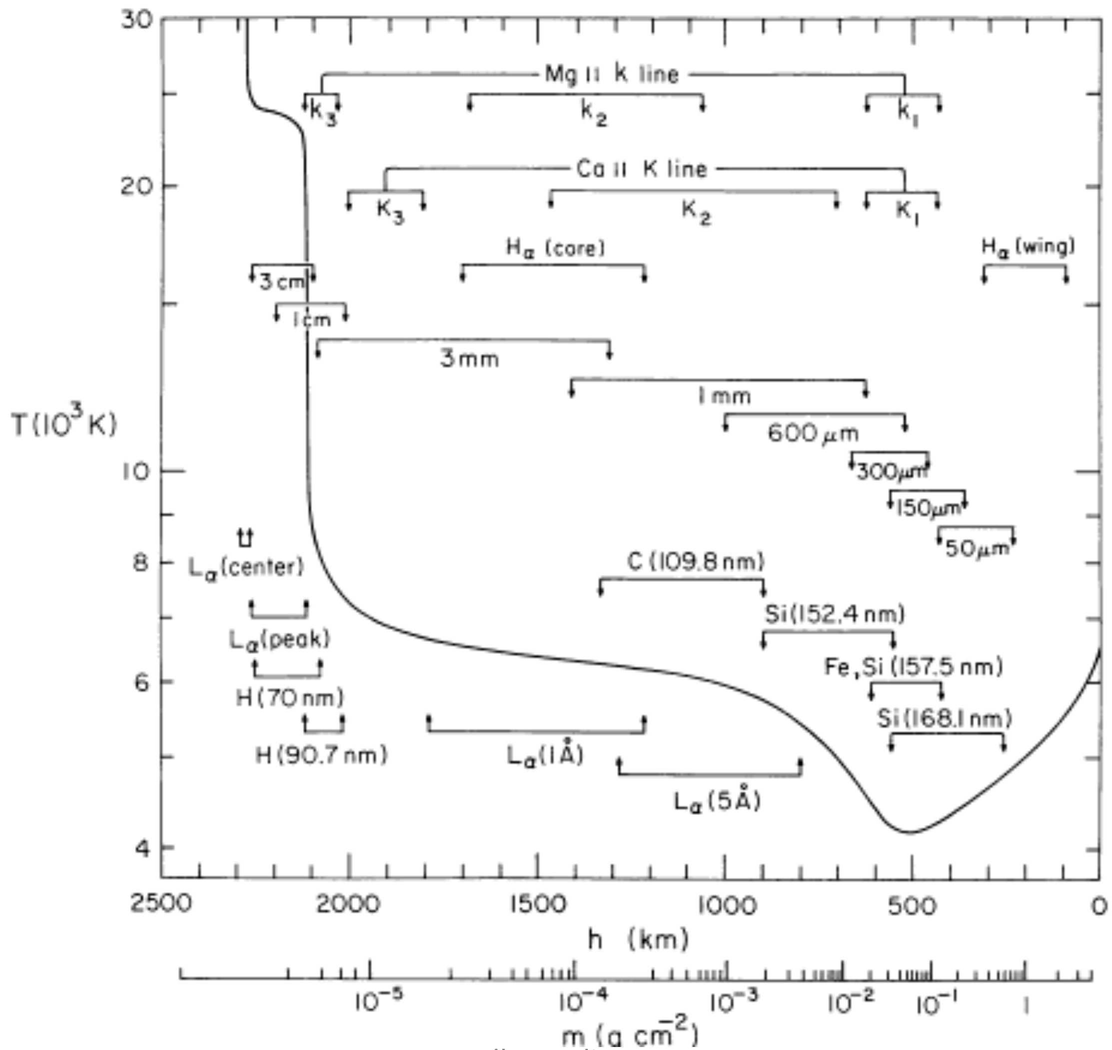


* 1.3mm survey of 92 YSO (3-5 Myr) stars in the σ Ori cluster (385 pc).
* Unresolved disk fluxes measured for 37 stars with disk masses plotted.
* First clear detection of evaporation of disks by a nearby hot star (O9).
* Dust masses decline with cluster age (1 to 10 Myr).
* Older clusters have insufficient dust mass to form cores of Jupiter-like giant planets (need 10x mass of Earth).
* Evolution of dust mass with age and environment important for testing planet formation scenarios.

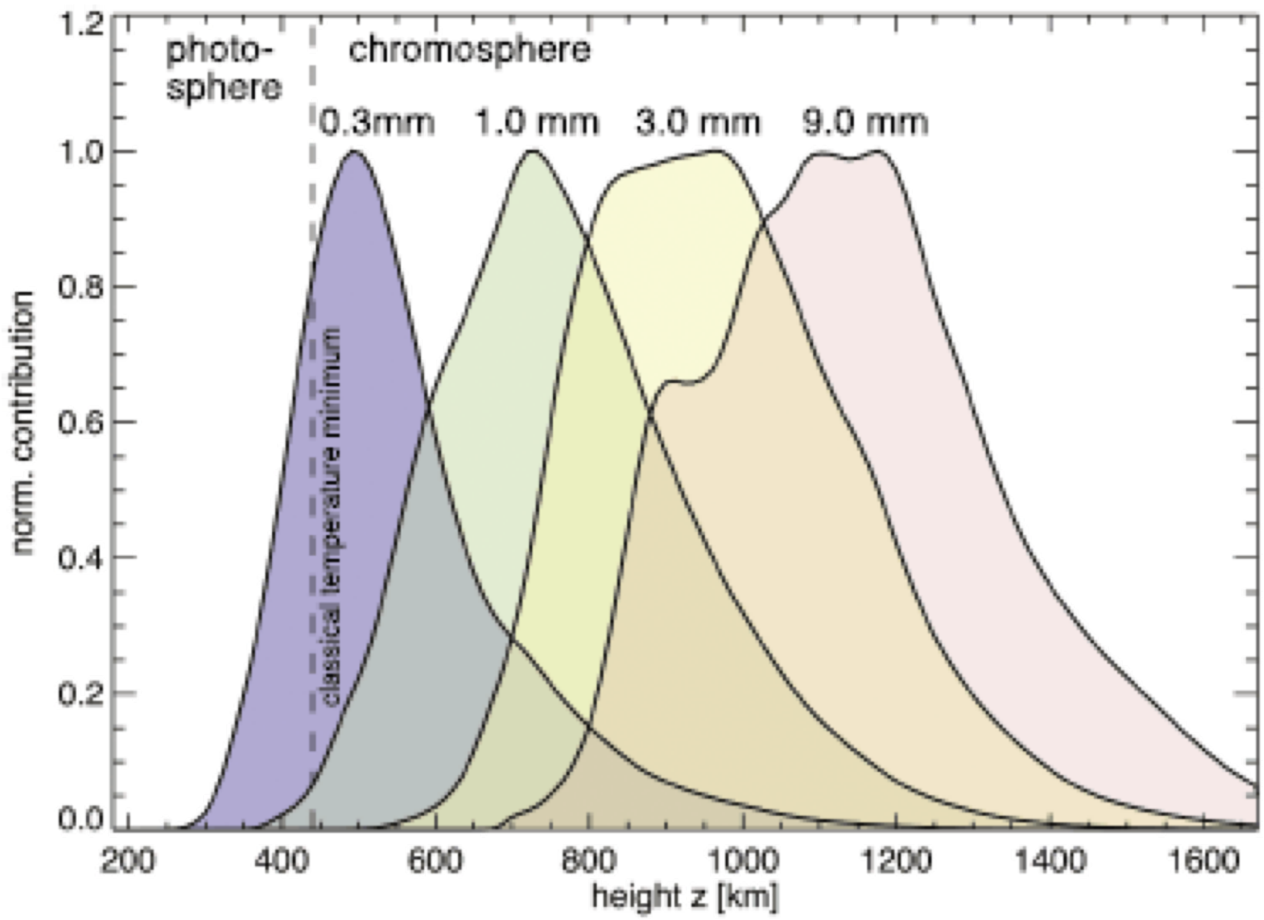
Thermal emission from ionized plasma (free-free = bremsstrahlung)

- Optically thick emission ($T_b = T_e \approx 10^4$) observed from the solar temperature minimum region, chromosphere and transition region.
- Optically thick emission from α Cen A, α Cen B, other dwarf stars with ALMA.
- Optically thick emission from red giants and supergiants (e.g., Betelgeuse).
- Optically thin emission from stellar coronae?

Millimeter and far-IR emission regions in the quiet Sun (Model C of Vernazza, Avrett, & Loeser 1981)

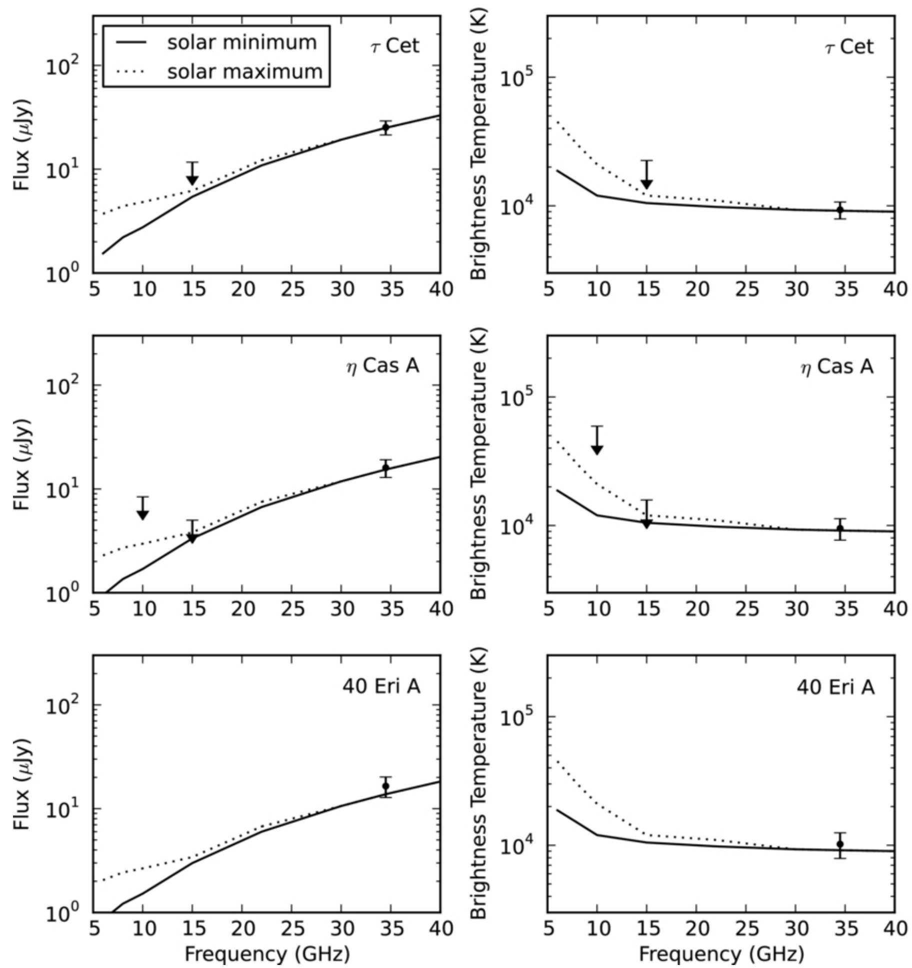


Contribution functions for continuum intensity at solar disk center (Wedemeyer et al. 2016)



JVLA detections of chromospheric emission from F-K dwarfs (Villadsen et al. 2014)

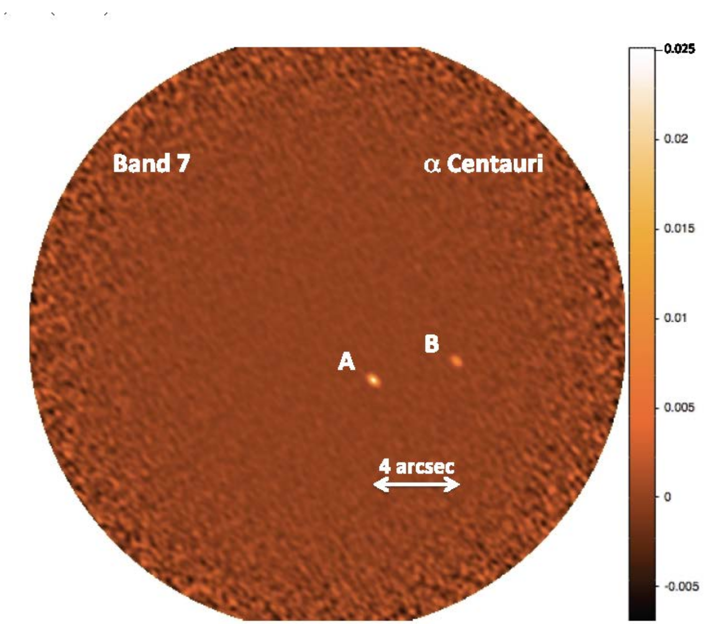
- Detections of η Cas (F9 V), τ Cet (G8.5 V), and 40 Eri A (K0.5 V).
- Solid lines are solar flux and T_B scaled to stars and their radii.
- 34.5 GHz free-free emission from chromospheres not wind or non-thermal but wider wavelength coverage needed.

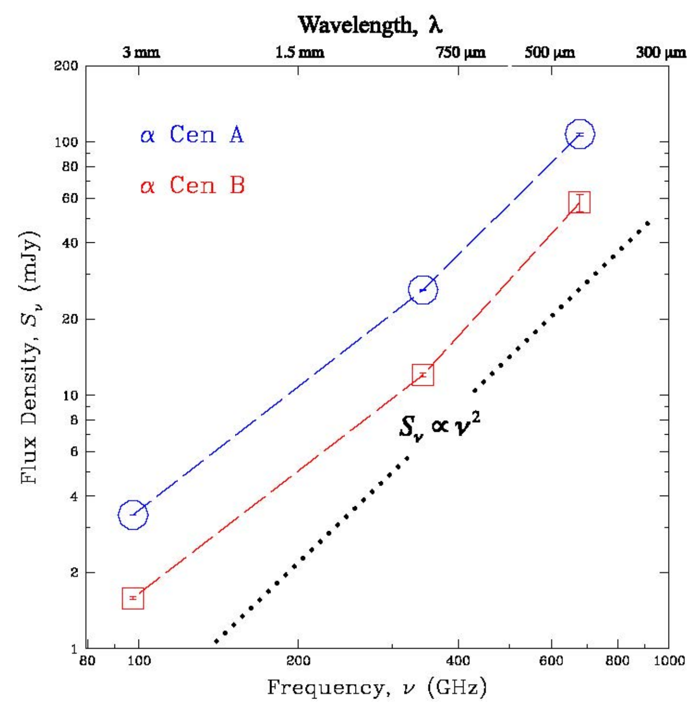


ALMA observations of α Cen A and B
(Liseau et al A&A 573, L4 (2015))

2 minutes exposure at 344 GHz

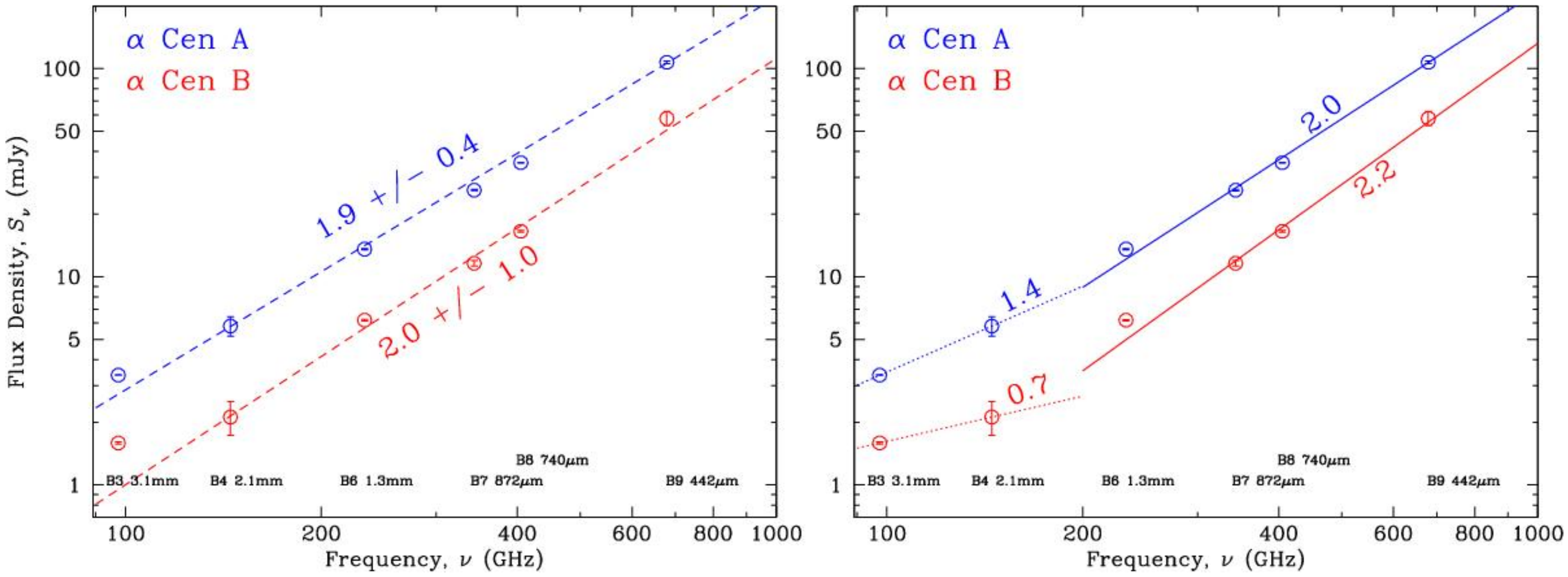
30 min at 97.5 GHz, 2 min at 344 GHz, 8 min at 679 GHz





First detection of a dwarf star at 3 mm with only 30 of 40 ALMA antennas.
Dotted line is predicted slope for optically thick free-free emission.

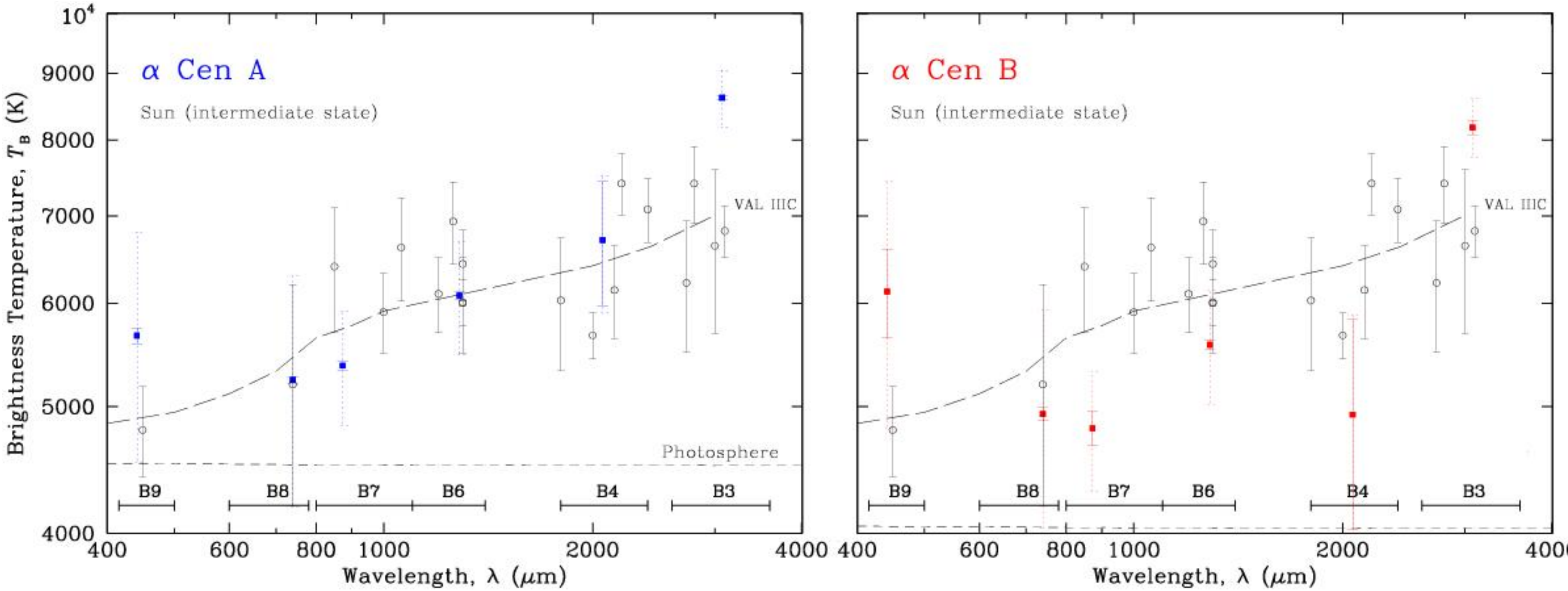
ALMA (bands 3-9) observed flux if α Cen A and B from 0.44 to 3.3 mm (Liseau et al. 2016)



Power-law slope of 2.0 expected for optically thick free-free emission at aproximatly constant T.

Increased flux at highest frequencies indicates that optical depth unity occurs at higher temperatures in the upper chromosphere and transition region.

Comparison of brightness temperatures obtained from ALMA fluxes with model chromospheres



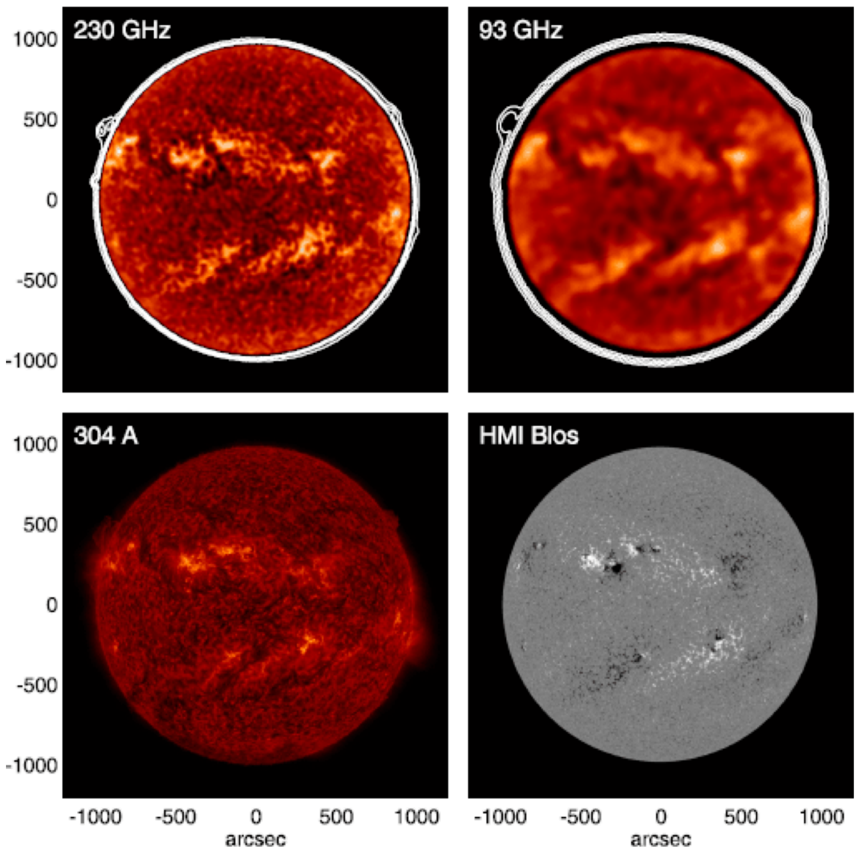
Since the emission is thermal from an optically thick plasma, the brightness temperature is a good measure of the mean temperature at optical depth unity across the inhomogeneous stellar disk.

The run of brightness temperature with wavelength samples the mean thermal structure with height. T_B lies above the predictions of photospheric models which do not include emission from chromosphere.

Comparison of ALMA and UV spectroscopy for studying stellar chromospheres

Property	ALMA (mm wavelengths)	UV spectroscopy
Plasma diagnostics?	Continuum LTE, CO rotate and recombination lines	Non-LTE (PRD for optically thick emission lines)
Spectral features	Free-free continua	Emission lines
Can one infer the thermal structure from the data?	$T_B(\lambda)=\int T_e dh \approx T_e(\langle h \rangle)$ (powerful technique)	$I_\nu=\int S_\nu dh \neq \int B_\nu(T_e) dh$ (complicated analysis)
Formation regions	Upper photosphere to upper chromosphere (increasing heights seen at shorter wavelengths)	Photosphere (wings), Chromosphere (peaks), Transition region (core)
Effect of non-MB electrons and ionization departures from equilibrium	Possible deviations from ionization equilibrium of H (affects optical depth scale)	Important for some lines (e.g., HeI, HeII, TR lines)
Measure magnetic field?	Yes (cont. polarization, gyrosynchrotron)	No (optical and near-IR much better for Zeeman splitting and ZDI)

Comparison of solar images: ALMA, UV (He II 304 Å) and line-of-sight magnetic field

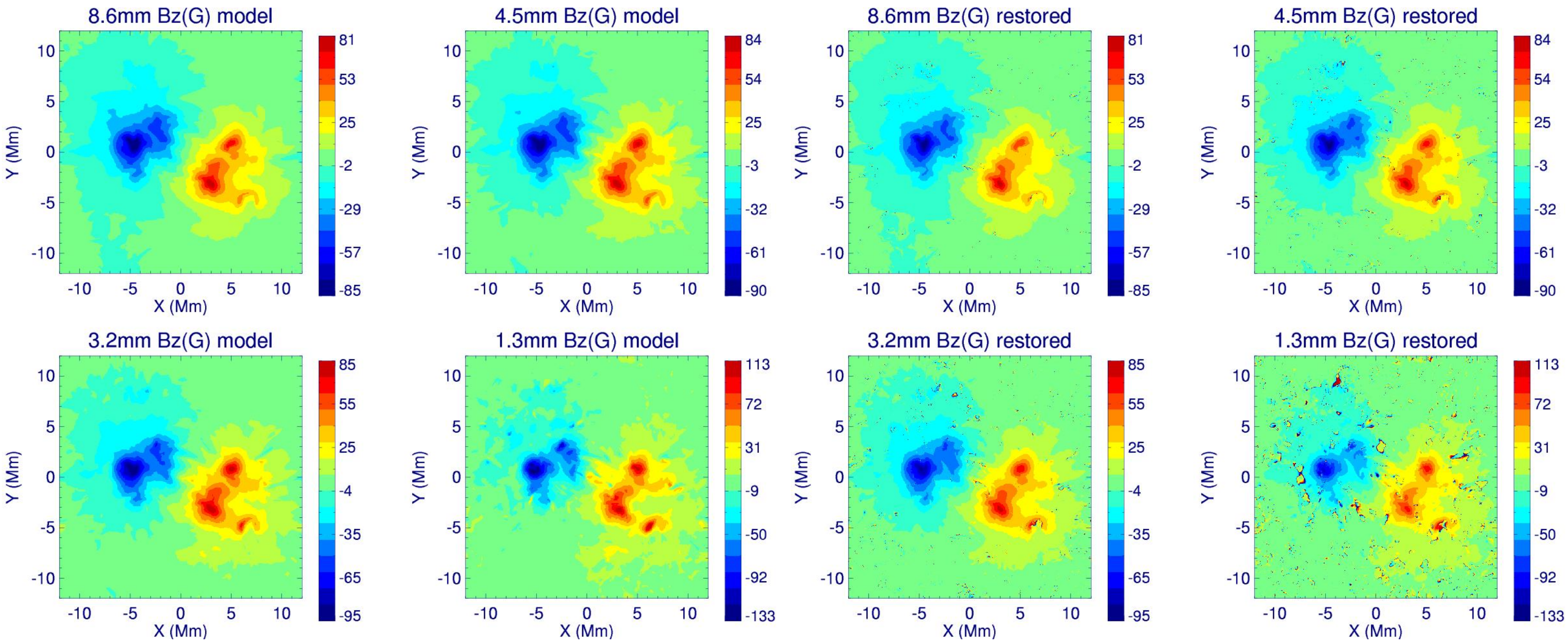


- Early ALMA images in bands 6 and 3 (single dish mapping).
- Similar structure indicates that mm flux contrast (temperature diagnostic) follows variations in magnetic fields and electron densities.
- White et al. (Solar Physics 292, 88 (2017))

Measuring chromospheric magnetic fields

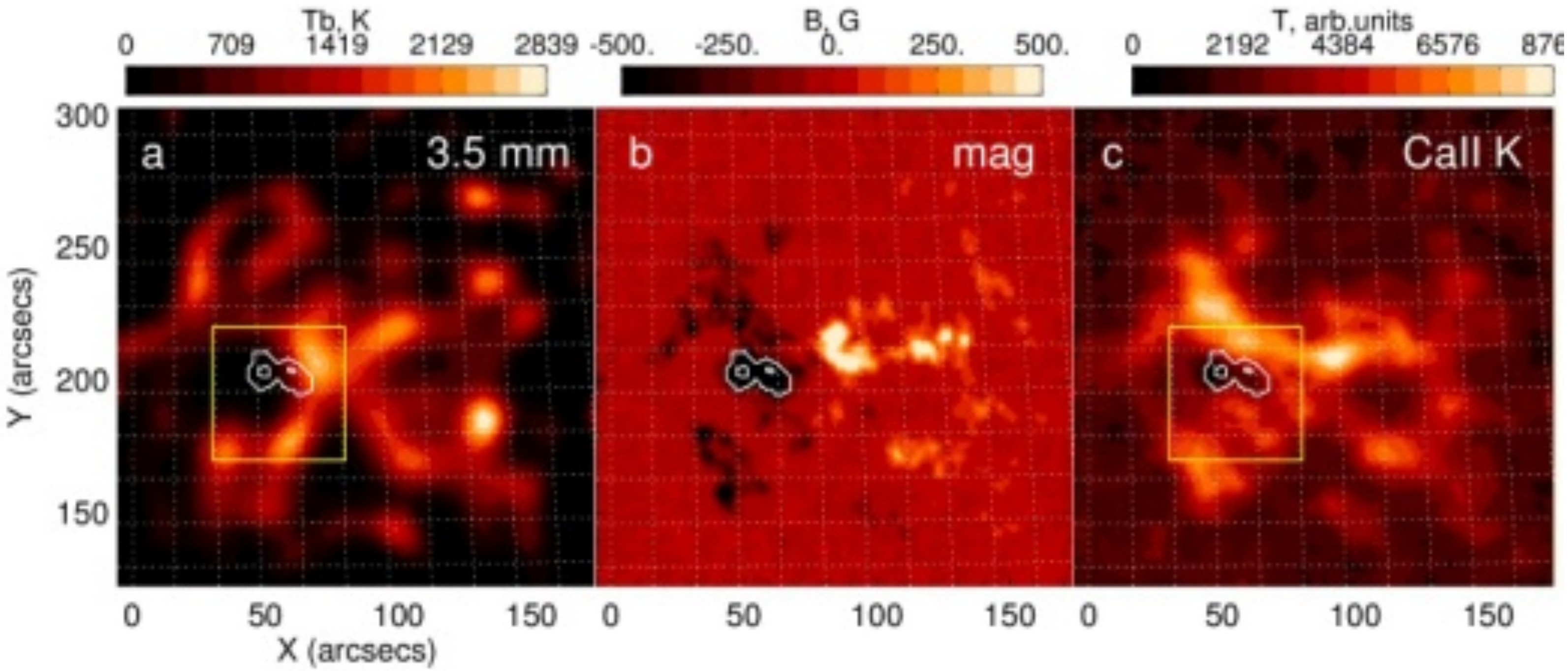
- Circular polarization of thermal free-free emission in a plasma with a longitudinal magnetic field: opacity larger in the x-mode than in the o-mode.
- Therefore, x-mode is optically thick at a higher layer where T is larger than is observed in the o-mode.
- Circular polarization: P=[f(x-mode)–f(o-mode)]/sum.
- $P \sim B_{long} / \nu \sim 0.00185 \lambda(mm) B_{long}(G)$ or about 2% at 1mm if B_{long}=1kG. Depends on thermal gradient (dT/dh) in the chromosphere.
- $B_{long} \sim P\nu/(dT/dh)$ in the chromosphere.

Circular polarization of mm free-free emission can measure chromospheric magnetic fields



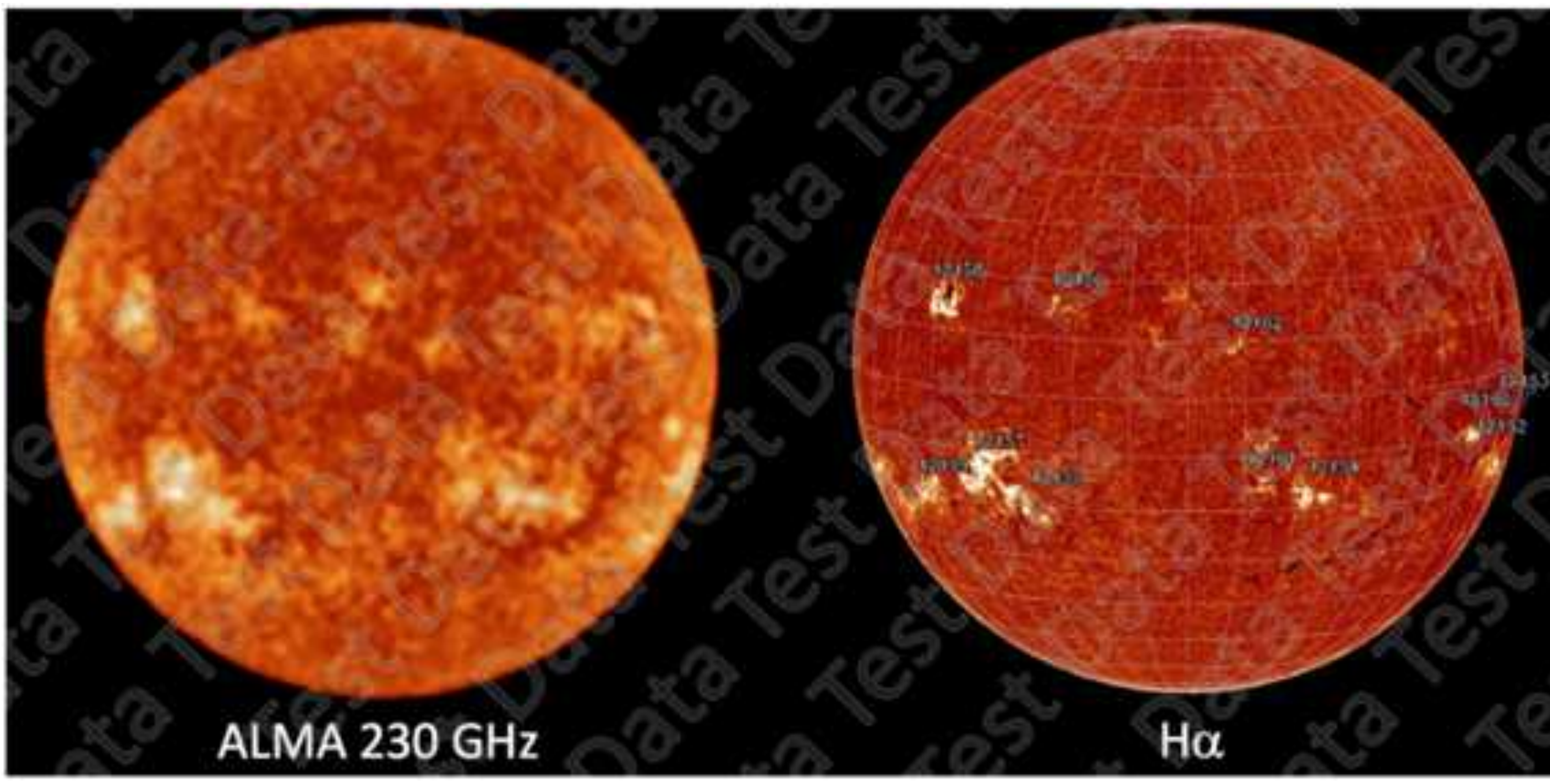
* Simulations of inferred magnetic field using a 3D non-LTE model atmosphere (Loukitcheva et al. A+A 601, A43 (2017)).
* Left panels: Line of sight (LOS) magnetic field in the model.
* Right panels: LOS magnetic field reconstructed from computed circular polarization.
* Requires excellent knowledge of instrumental polarization (<1 %).

Comparison of 3.5 mm (BIMA array) image of a solar region near a sunspot with magnetic field and CaII K (Loukitcheva et al. A+A 561, A133 (2014))



Correlations of mm emission with magnetic field and chromospheric emission line flux not exact but close.

Comparison of a an ALMA single disk solar image at 1.3 mm with an Hα image (Wedemeyer et al. 2016)



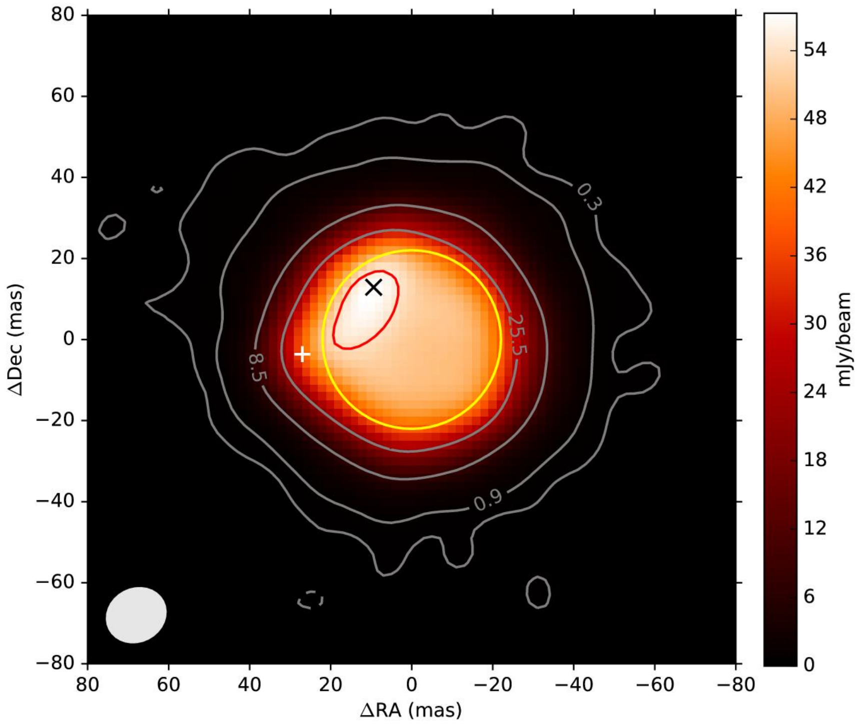
Thermal structure and heating rates of stellar chromospheres

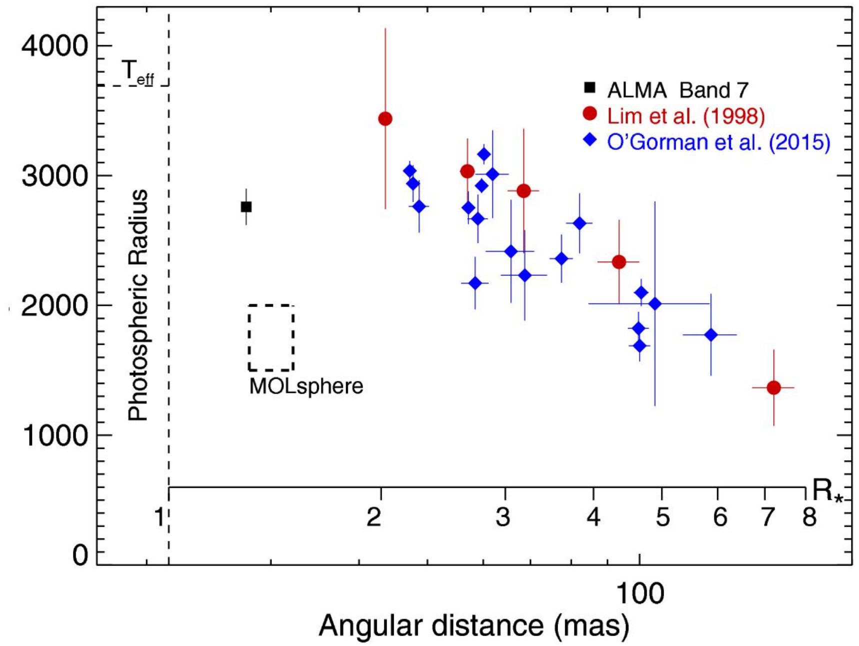
- Opacity: electron-ion and H^- free-free (thermal, $k \sim 1/\nu^2$) → Te(h), which increases with increasing ν.
- A simple test of theoretical and semi-empirical models based on UV spectroscopy which biased to hotter, denser regions.
- Comparing empirical T(h) with theoretical models with no heating → heating rate as f(h). Which heating mechanism?
- Possible problem: H may not be in steady-state ionization equilibrium (due to shocks or waves).
- Stellar chromospheres are multicomponent: mm-wave continuum emission is linear in T, but UV emission lines very nonlinear in T.
- CO rotation lines (e.g., 6→5 at 691 GHz) are good indicators of the coldest gas in the T minimum region and above.

Do A and B stars have chromospheres?

- Chromospheres are observed in stars as early as A7 IV (Altair) and possibly A5 V from UV emission lines, but the UV continuum rapidly brightens for hotter stars making it hard to see UV emission lines.
- Chemically-peculiar AB stars and even young O7 stars are radio bright and many also emit X-rays (winds or coronae?)
- ALMA is a good search tool because mm emission is linear with T and opacity source at mm wavelengths should be mostly thermal free-free.

ALMA observations of Betelgeuse (M2 Ia) at 0.89 mm (O'Gorman et al. A+A 602, L10 (2017))





* Resolution 14 mas compared to optical photosphere diameter 43 mas.

* Hot spot 1000 K hotter than mean disk indicating localized heating.

* Mean disk at 0.89 mm shows T_B=2760±140 K well below T_{eff}=3690±54 K.

* T_B at 1.3 R below T_B at 2R indicating heating at 2R but not 8000 K.

* Much more can be learned from Betelgeuse and other cool giants and supergiants.

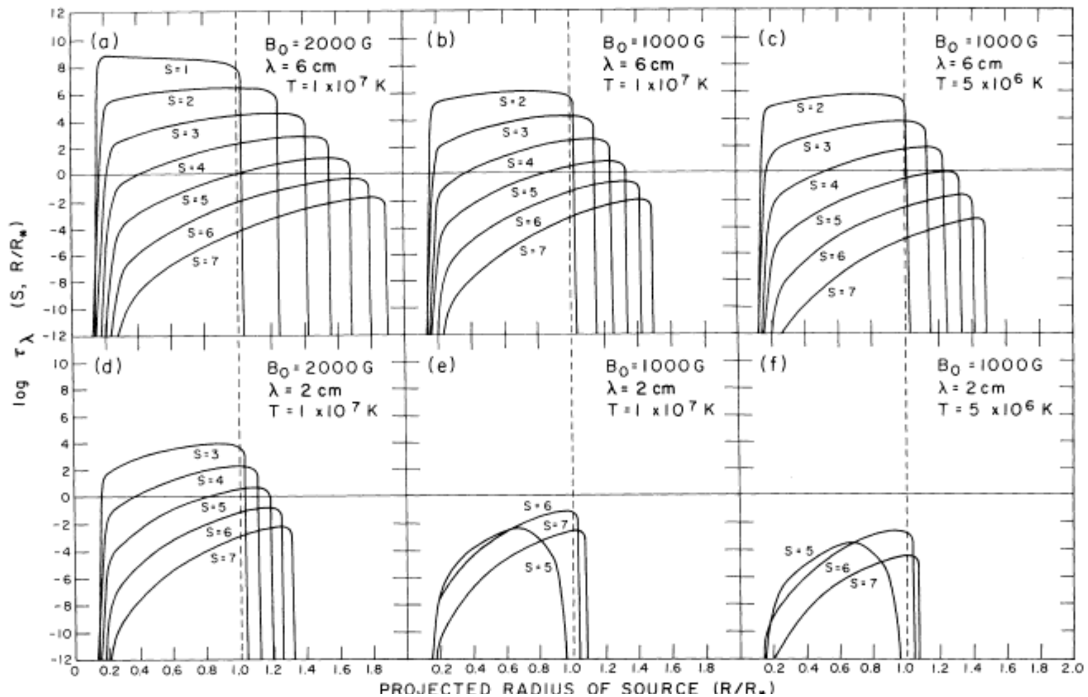
For the future: studies of spatial and temporal variability of stellar atmospheres

- Rotational modulation: monitoring the mm flux over several rotations should indicate presence of hotter active regions and cooler starspots.
- Doppler imaging of optical emission lines (correlated with ALMA observations) could indicate sizes of starspots and (perhaps) active regions.
- Chromospheric thermal structure above sunspots poorly known and unknown above starspots.
- Semi-empirical models of active regions will measure their heating rates.
- Search for thermal structure of pulsations and shocks in luminous giants and supergiants.

Gyroresonance emission: free-free emission by thermal electrons in a magnetic field

- Emission at a low harmonic ($s<10$) of the gyrofrequency: $\nu=2.8\times10^6\, sB$ [Hz].
- Circular polarization because x-mode has larger optical depth than o-mode.
- For Sun see gyroresonance emission from transition region or low corona above kG magnetic fields. See the layer where the highest harmonic is optically thick (usually $s=3$ to 5).
- Probably important for low activity stars.

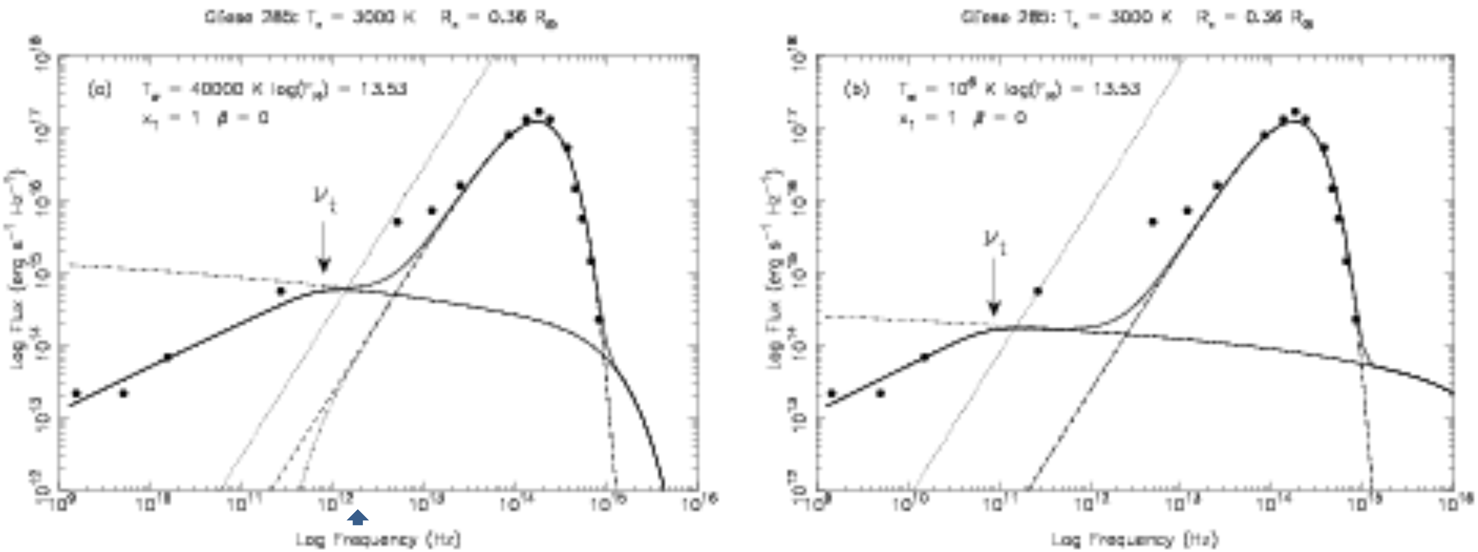
Detection of 6 cm emission from Chi¹ Ori (G0 V) and UV Cet (dM5+dM5) by the early VLA (Gary+Linsky 1981)



- Fit with model of gyroresonance emission from harmonics s=1-4, coronal temperatures (0.5-1.0x10^7 K), extrapolations of photospheric magnetic fields (1000-2000 G).
- Model fits the 6 cm data but not unique. Could also be fit with T_b=10^8 K gyrosynchrotron emission from a portion of corona (Linsky+Gary 1983)

Can ALMA and JVLA measure mass-loss rates from dwarf stars?

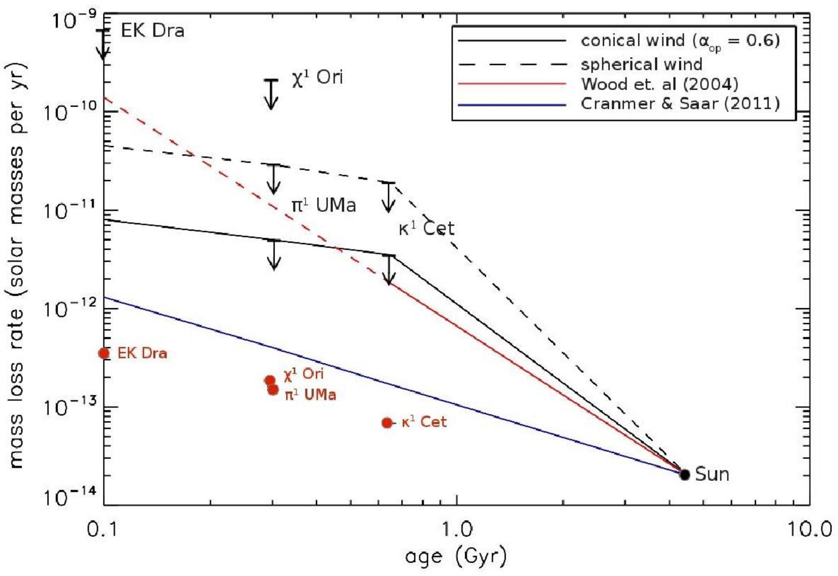
Predicted wind emission at mm wavelengths: van den Oord & Doyle (A&A 319, 578 (1997))



Figures show observed (dots) and model flux for YZ CMi (dMe) with wind temperatures 40,000 K (left) and 1,000,000 K (right). The thick line is the flux from the star and wind. ν_t is the frequency at which the wind becomes optically thin (thin at lower frequencies). These models are for an assumed mass-loss rate of $1\mathrm{x}10^{-10}$. Smaller mass-loss rates decrease the wind contribution and ν_t moves to higher frequencies. The model ignores likely gyrosynchrotron emission at cm wavelengths.

Upper limits on mass-loss rates from young solar-like stars from JVLA 6 and 14 GHz data

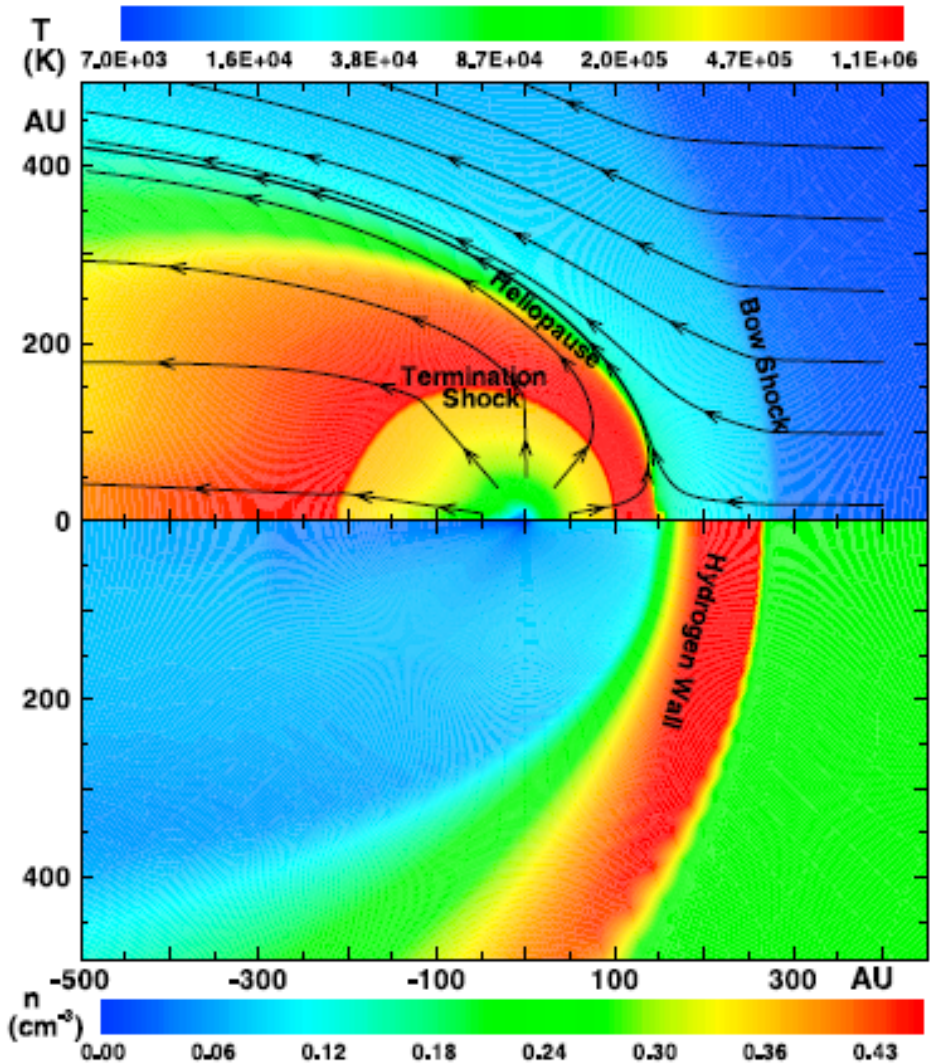
- Observations of young solar-mass stars by JVLA and ALMA (100 GHz for one star).
- Mass-loss rate upper limits assuming optically thick wind with $T=10^6$ K, v=400 km/s.
- Hard to separate wind emission from chromosphere (free-free) and gyrosynchrotron emission.
- Opportunity for ALMA observing at higher frequencies (no nonthermal emission and chromosphere T_b smaller).



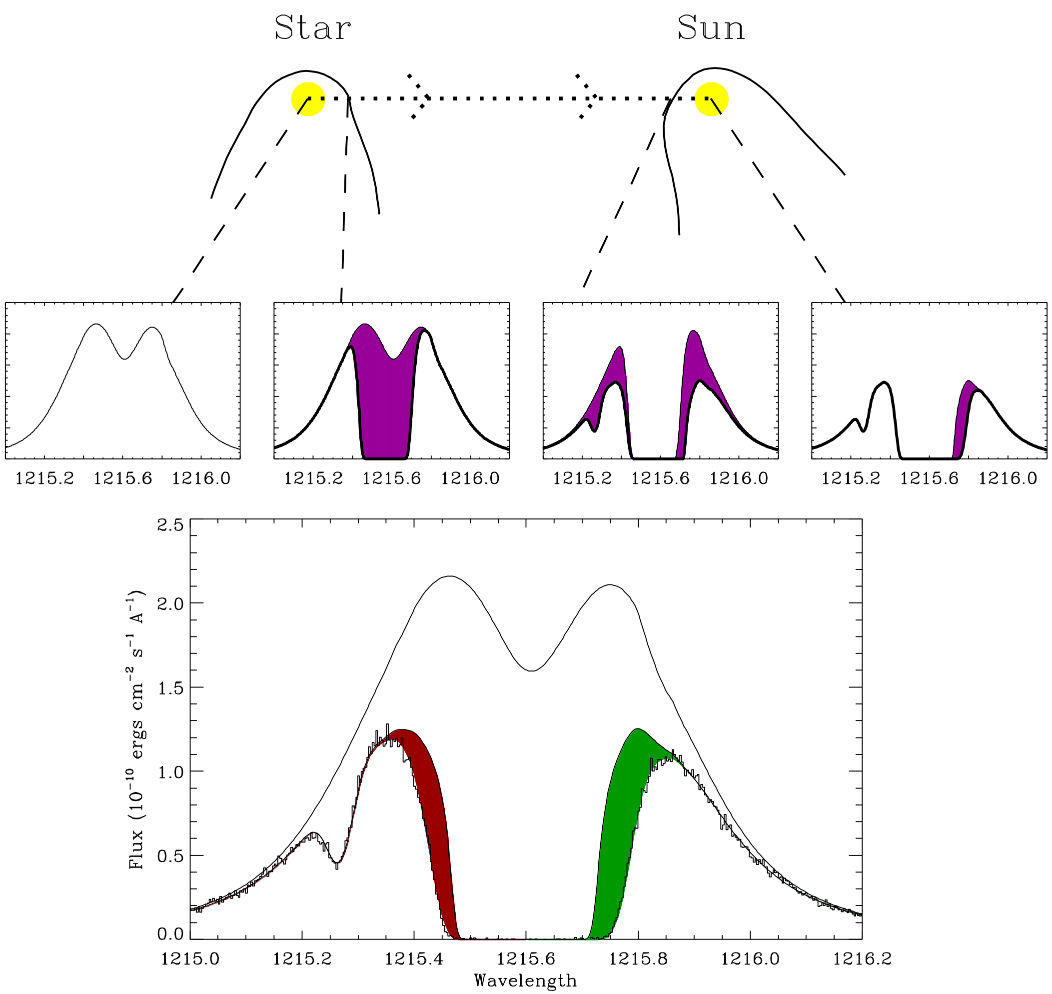
Red line: mass-loss rate from astrospheres.
Blue line: Alfven wave driven wind theory.
Red dots: rotational evolution model.
Fichtinger et al. (A&A 599, A127 (2017)).

What is an astrosphere?

- Stellar analog of the heliosphere.
- Interaction between the stellar wind and partially ionized ISM gas flow controls the physics.
- Solve the hydrodynamic equations for ions and neutrals, including charge exchange reactions between stellar wind ions and ISM neutrals.
- Magnetic fields will modify the plasma properties.
- Figure from Müller & Zank (2004). Original work by Baranov et al.
- IBEX data suggest that there is no bow shock in the heliosphere because velocity difference is too small.



Journey of a Lyman-α Photon



Detailed central profile of late-type star has little influence since at the core of absorption.

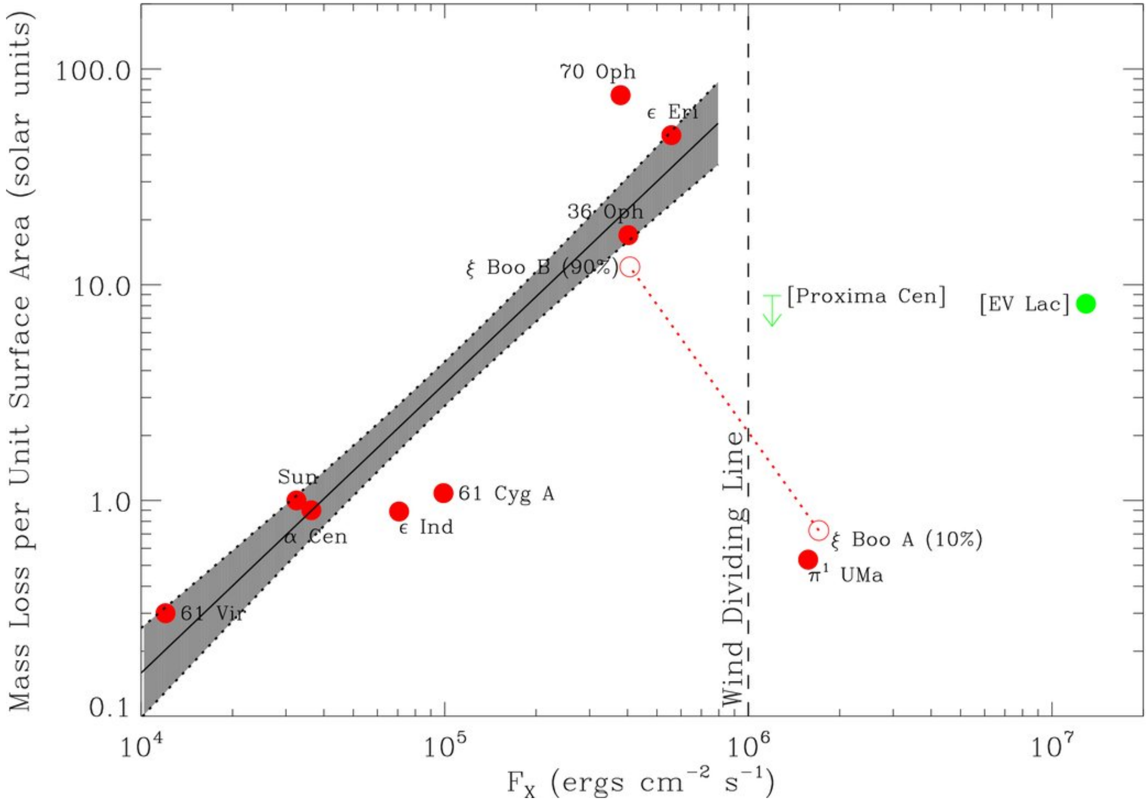
log N_H(LISM) < 18.7, otherwise obliterates any helio- or astrospheric signature.

Nearby DI line critical to constraining fit of LISM absorption (and constancy of D/H in Local Bubble).

Since HI is decelerated at heliosphere, the heliospheric absorption is always redshifted and the astrospheric absorption is always blueshifted.

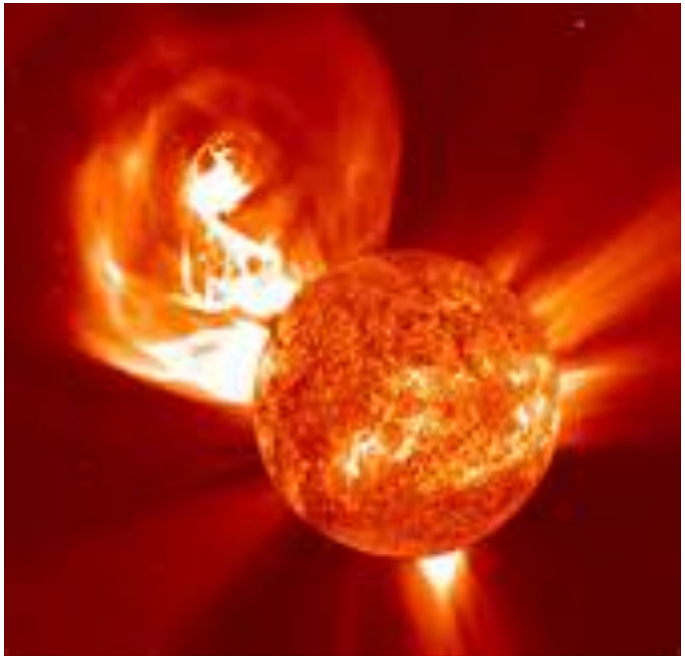
Wood et al. (2002)

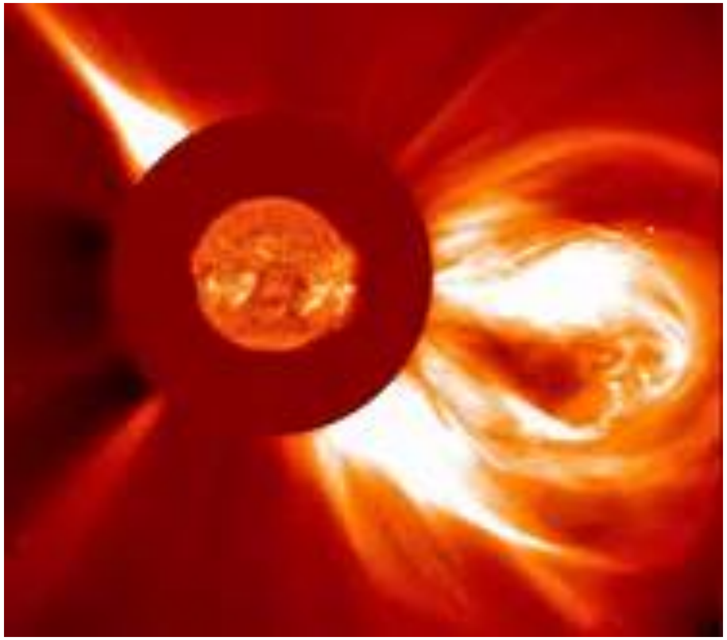
Mass-loss rates from additional Ly-α absorption in the stellar hydrogen wall (Wood et al. ApJL 781 (2014))



Mass-loss rate for EV Lac is 1.5×10^{-14} solar masses/yr. For Proxima Cen the upper limit is 3×10^{-15}. We need to measure many more mass-loss rates for M dwarfs. Hint to HST TAC.

Examples of coronal mass ejections (CMEs) observed in the optical by the LASCO instrument on SOHO spacecraft





Is mass loss from active dwarf stars constant or dominated by transient events?

- Osten & Wolk (2015): Estimate the mass loss rates in flare associated coronal mass ejections (CMEs) based on stellar flare rates and their estimated equipartition between radiation (bolometric flare energy) and CME kinetic energy.
- Young Sun: 450-2000 times present solar steady mass-loss rate. Big effect on protosolar disk and erosion of exoplanet atmospheres.
- Active M dwarfs: 50-3500 times present steady solar rate.
- High mass-loss rates consistent with scaling from magnetic filling factors (Cranmer 2017) and theoretical models).
- Test by observing stellar CMEs (Type II bursts at 10-1000 MHz)
- Test at mm wavelengths by separating free-free wind emission from free-free chromospheric emission. A very difficult challenge.

Nonthermal radio emission processes: gyrosynchrotron, electron-cyclotron maser, beams, shocks, etc.

Non-coherent emission from relativistic electrons in magnetic fields

- Gyrosynchrotron emission: nonthermal coronal electrons emitting at $s\nu_{cyclo}$ = s0.0028B, where s>10.
- Nonthermal electrons produce much brighter emission than thermal electrons .
- Optically thick gyrosynchtron emission has $T_B \approx 10^9$ K compared to $T_B \approx 10^7$ K for gyroresonance emission.
- At 1 mm, s=100 for B=1 kG (electrons very relativistic).
- Peak wavelength for gyrosynchrotron emission indicates local magnetic field strength (where emission goes from being optically thick to optically thin).

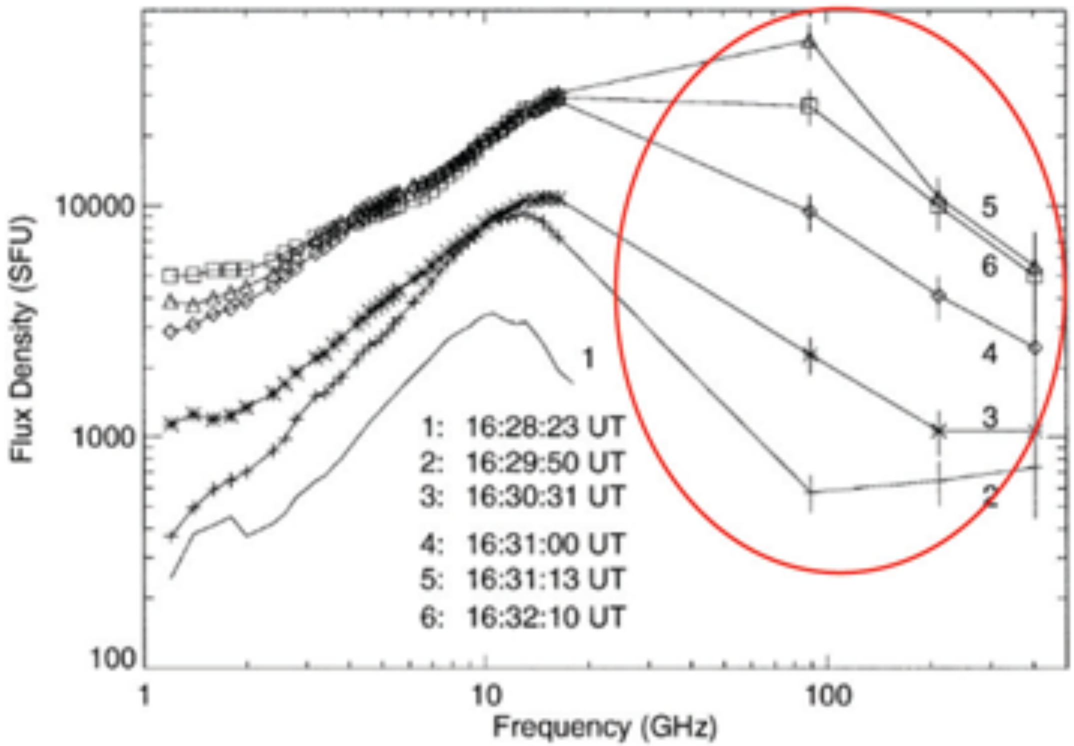
Flares – heating and electron beams

- Flares heat and evaporate chromospheres and upper photospheres: increase T(h) and decrease neutral hydrogen column density at top of chromosphere.
- Measure ΔT(h) to infer flare heating rate in chromosphere.
- Do electron beams dissipate most of their energy in the chromosphere or the photosphere?
- Look for evidence of chromospheric heating before impulsive phase of flares. Precursor heating.
- Simultaneous ALMA and VLA (mm→cm data) → gyrosynchrotron spectral energy distribution →

  B and emitting area if assume $T_B = 10^9$ K.

Solar flare at different times showing gyrosynchrotron emission with peaks at 10→100 GHz (Raulin et al 2004)

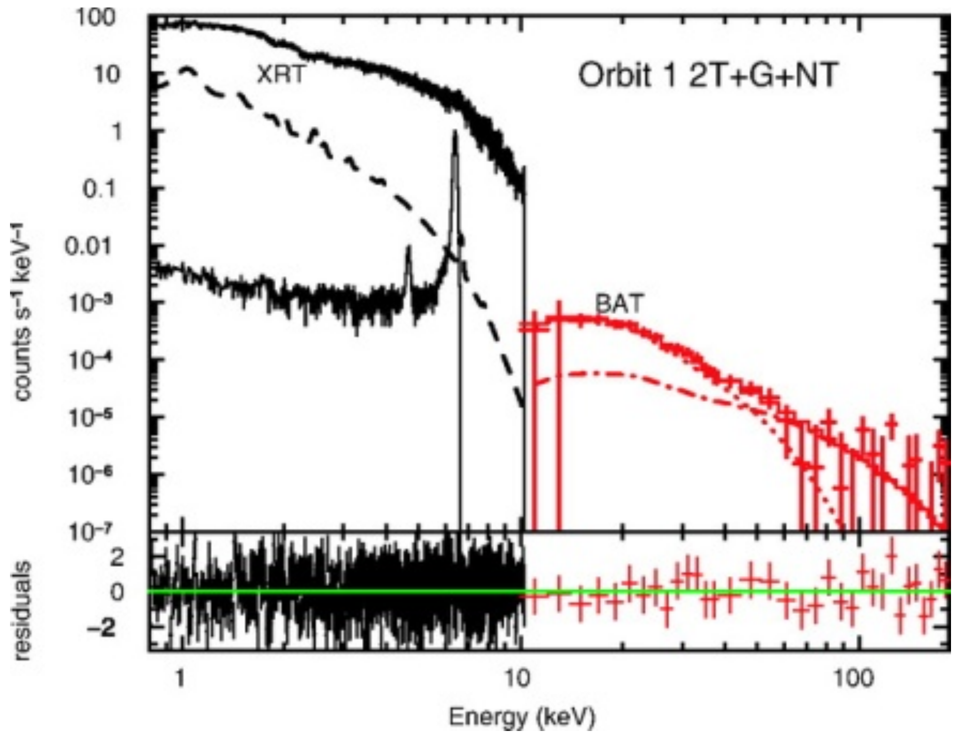
* Solar X5.3 flare with white light, γ-rays, radio, X-ray data.
* Map of mm emission shows acceleration site.
* Emission at 405 GHz shows gyrosynchrotron emission from highly relativistic electrons (s≈100, B≈1000 G).
* ALMA can study superflares on nearby stars.



Flares on active stars (young, rapidly rotating, dMe) are more energetic and likely have higher energy relativistic electrons. This will place emission peak at higher frequencies in ALMA range.

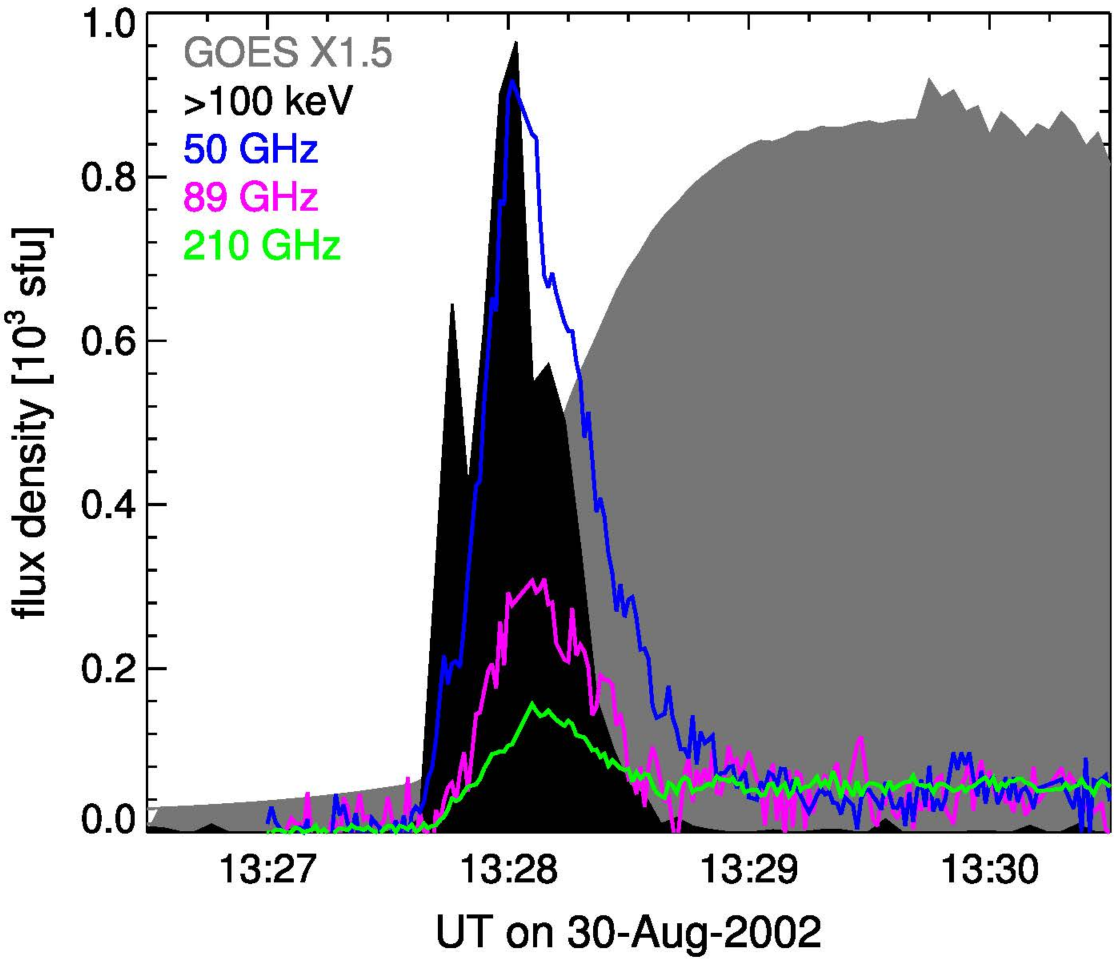
Stellar superflares are far more energetic than solar flares

- Superflare SED on II Peg can be interpreted as a multi-thermal plasma with T_{hot}=300MK or a thermal + non-thermal plasma.
- Plot shows probable non-thermal component (dashed-dot line).
- Log L(non-thermal) = 40.2
- Gyrosynchrotron emission from extremely energetic electrons will peak in ALMA wavelength range.



Osten et al (ApJ 654, 1052 (2007)) observation of II Peg with HST and SWIFT/BAT.

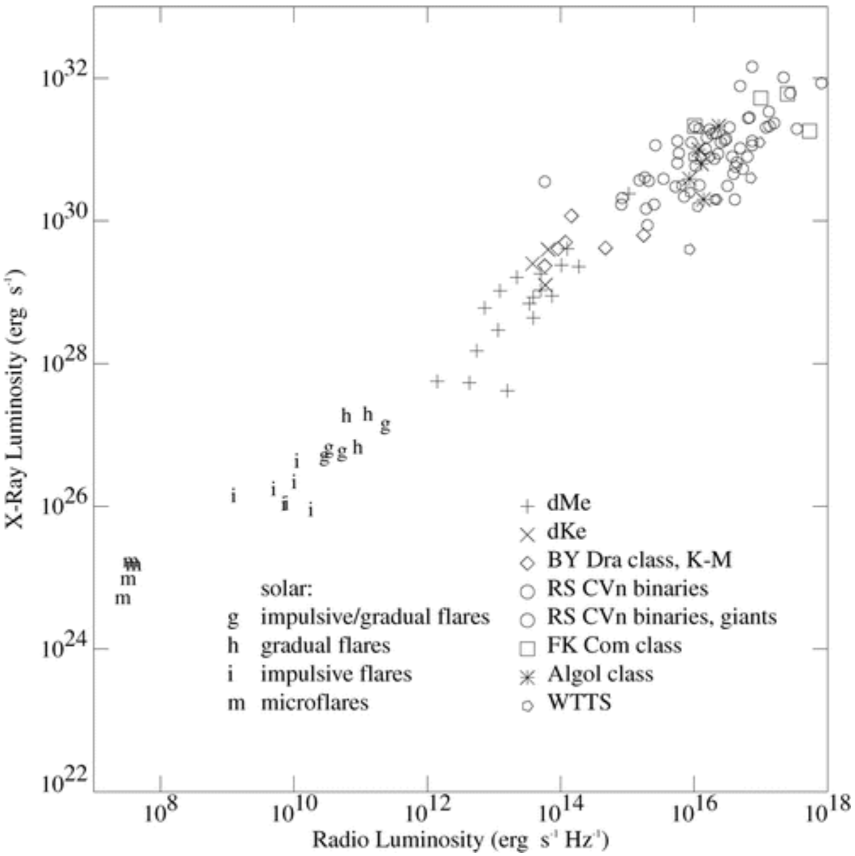
For solar flares, the time scale for mm emission is similar to hard X-rays and then a tail like soft X-rays



Krucker et al. (A+ARev 21, 58 (2013)

Gyrosynchrotron emission from relativistic electrons is typically observed from magnetically active stars

- Flares on G to late-M stars and "quiescent emission" from rapidly rotating stars with strong magnetic fields.
- Benz+Güdel (1993) showed that thermal X–ray and non-thermal radio emission (5-8 GHz) are correlated over 10 orders of magnitude.
- Why? Not same thermal electrons. Maybe simultaneous heating and particle acceleration. Other models are proposed.
- Need long-term X-ray and radio monitoring over a wide wavelength range to understand why. ALMA can observe emission from highest energy electrons.



Güdel (ARAA 40, 217 (2002))

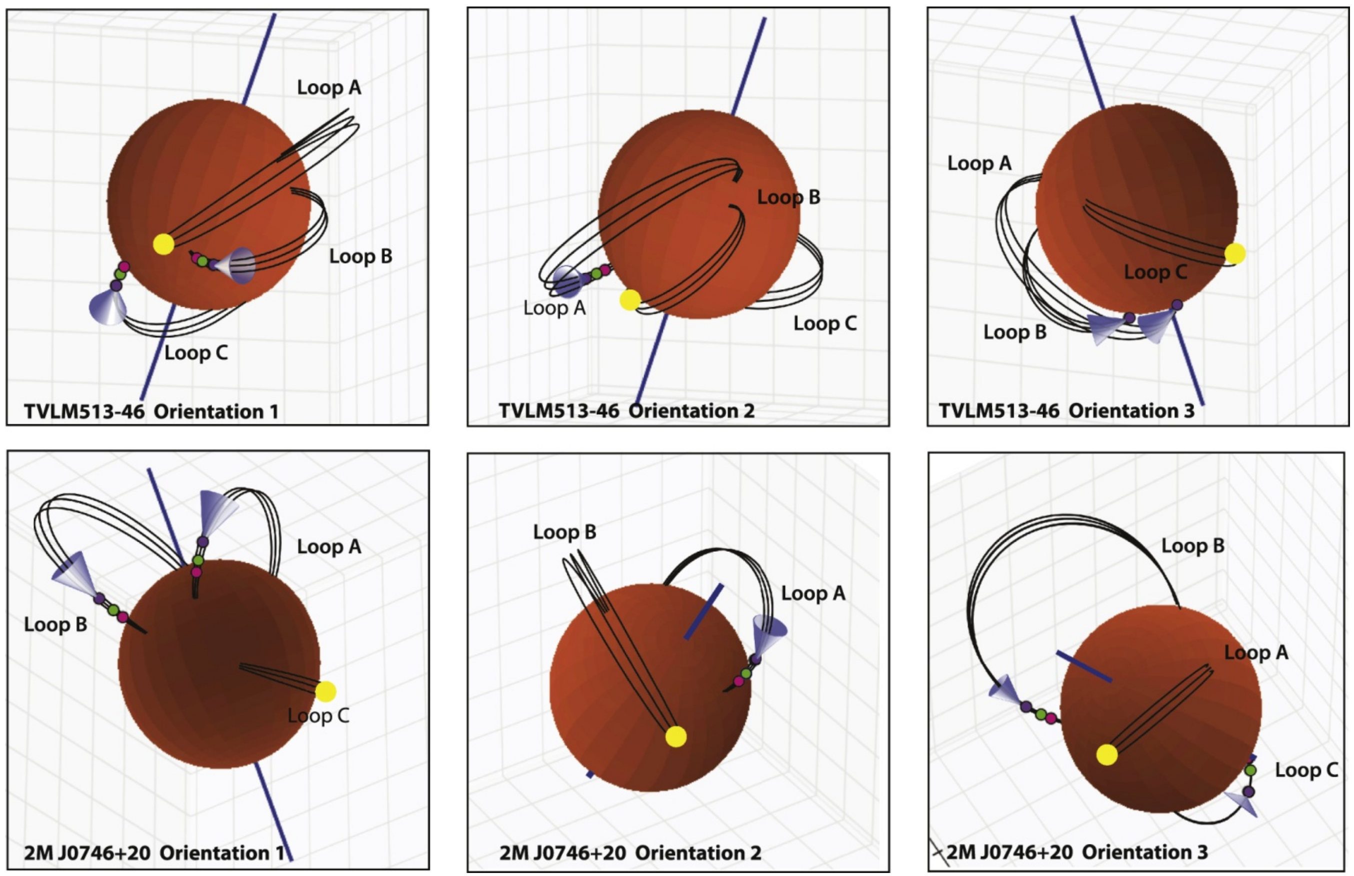
Radio emission from the coolest stars, brown dwarfs, and planets is very different from the warmer stars

- M0-M7 dwarfs have kiloG magnetic fields, flare, and are variable gyrosynchrotron radio emitters.
- Late-M, L and T stars are fast rotators, often show very strong 100% circularly polarized pulsed emission at 1.4-10 Ghz, but weak X-ray, Hα, and gyrosynchrotron (Hallinan, Kao, Lynch, Osten, Berger, etc.).
- Periodic pulsed emission observed at the stellar rotation period.
- Probably beamed along field lines from electron-cyclotron maser sources at the cyclotron frequency [ν(MHz) = 2.8 B(kiloG)].
- Observed by JVLA and the only way of measuring magnetic field strengths (probably dipolar) in very cool stars and brown dwarfs.
- ECM emission excited by electron beams spiraling into converging magnetic fields. The energy source is unknown, but could be auroral electric currents in mostly neutral atmospheres.

Continuum and pulse emission from ultra-cool dwarfs (Lynch et al 2015)

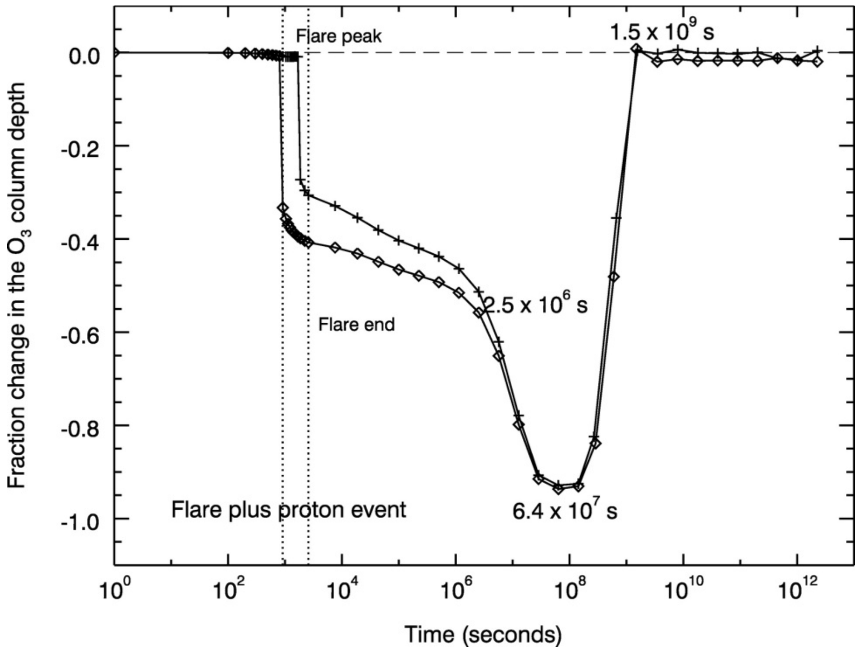
- About 10% of ultra-cool stars are radio detected by JVLA at 1.4-10 GHz (Berger, Hallinan, Osten, and others)
- Emission is both continuous (optically -thin gyrosynchrotron emission from mildly relativistic electrons) and bright pulsed (electron-cyclotron maser instability (ECM) emission).
- ECM source likely near foot point of a magnetic loop where the strong magnetic field lines are converging.
- Model with strong magnetic fields (2-3 kG) in a few loops.
- Need deeper JVLA observations to measure Stokes IVQU to determine plasma properties where pulse emission originates.

Coronal loop (2-3 kiloG) models for 2 ultracool dwarfs showing location of electron-cyclotron maser instability (Lynch et al. 2015). Yellow dots show location where beaming is to observer. Other models have been proposed.



Strong solar flares typically produce CMEs (solar mass ejections)

- CMEs with energetic protons and shock accelerated electrons cause emission at the plasma frequency and its harmonics.
- Type II bursts drift in frequency as the electron beam moves up in the corona to lower densities.
- Measure shock speed + density.
- Impact on planet atmospheres can be catastrophic (atmospheric erosion and ozone depletion) , especially for tidally locked planets that are slowly rotating with weak magnetic fields.

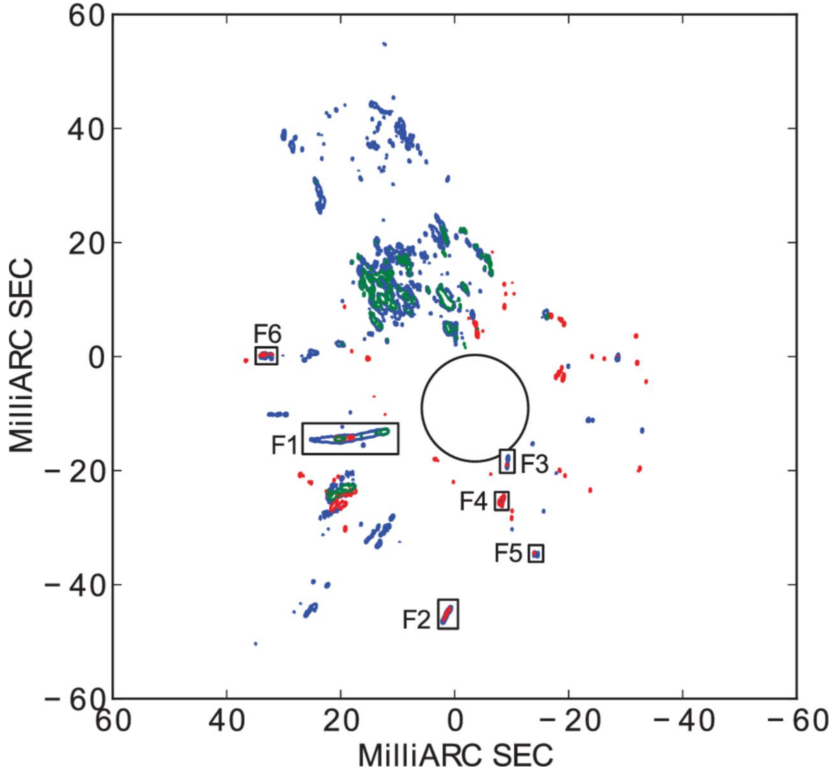


Effect of XUV radiation and CME protons from a large flare on AD Leo (M3.5 V) impacting the atmosphere of an Earth-like planet in its HZ (0.16 AU). CME protons form NOx that depletes ozone for 50 years (Segura et al. Astrobiology 10, 751 (2010)).

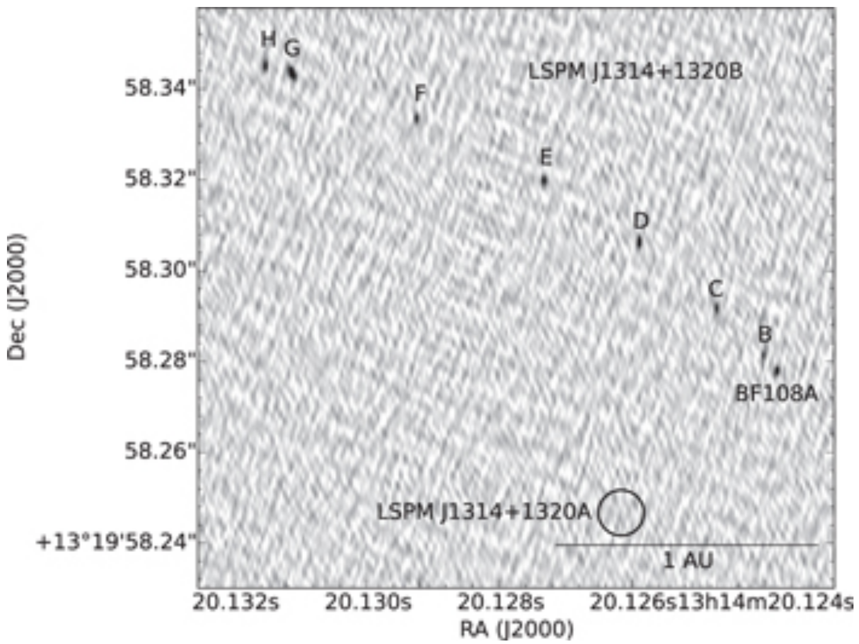
Can stellar CMEs be detected by low frequency radio emission?

- Stellar Type II bursts have not yet been detected but would be a direct indicator of stellar CMEs. Impact rate and energies needed for assessing habitability of exoplanets in their liquid water "habitable zone".
- For expected shock speeds and coronal densities, expect to see Type II bursts (with drifts) in the 10 MHz to 1 GHz range. Expect $T_b > 10^{14}$ K.
- Searches underway at 10-190 MHz with LOFAR (Crosley et al. 2016, Osten & Wolk 2015, others),
- JVLA (P band 230-470 MHz), SKA, and Murchison Widefield Array should be useful for detecting stellar CMEs.

Two examples of the power of high-resolution VLBI/VLBA imaging



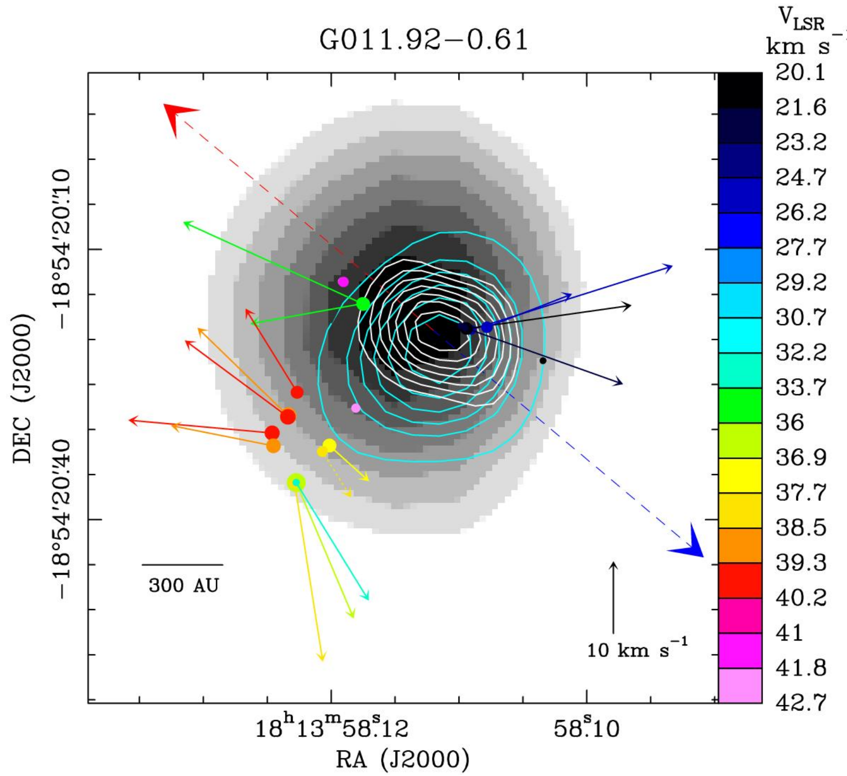
VLBA (7 and 3 mm) observation of VY CMa showing polarized SiO masers. Constraints on polarized maser emission models. Richter et al. (2016).



VLBA (7 GHz) observation of proper motion and parallax of the ultracool binary LSPM J1314. Separation 130 mas and beam size 2.9x1.2 mas. Secondary star >30 times brighter. Why? No planet reflex motion.Forbrich et al. (2016).

Combined VLBA and JVLA study of outflows from high mass PMS stars

- JVLA ionized wind emission at 6.2 GHz (grey) and 13.1 GHz (cyan) with water masers (dots). High sensitivity of JVLA critical.
- VLBA (22 GHz) maser kinematics (arrows) from proper motion monitoring with 0.42 km/s resolution.
- 3D velocity and spatial structure of the molecular gas compared with the ionized gas.



Moscadelli et al. A&A 585, A71 (2016)

Some major opportunities in astrophysics that stellar radio observations can now address

- What are the physical processes by which host stars control the evolution and habitability of their exoplanets?
- How do young stars and their planets form and evolve in their common disk environment?
- How is stellar magnetic field energy converted into heat, high energy particles, and mass loss?
- What physical processes control mass loss from stars across the H-R diagram and the effects of mass loss on stellar evolution?

Is the nfield of stellar radio astronomy prepared for the future?

• Telescopes/instruments	Yes
• Data analysis software	Yes
• Scientists and engineers	Yes
• Vision	Yes
• Enthusiasm	Yes
• Resources/funding	???

Conclusions – What I look forward to learning at this conference

- Radio observations can measure essential properties of astronomical sources that cannot be obtained at other wavelengths.
- Observations at radio wavelengths can address major problems in contemporary astrophysics.
- New observational capabilities of ALMA, JVLA, SKA, etc. will provide amazing results.
- Who will make the discoveries?

Thank you for your interest and thanks to the committee that has organized this Stellar Radio Astronomy workshop.

Radio Brightness Temperature: T_B (K)
$L = 4.7\times10^9\,(1\mathrm{mm}/\lambda)^2\,(R/R_{sun})^2\,T_B$ (erg/s/Hz)

- Free-free (bremsstrahlung) continuum thermal emission has 3 components:

(1) optically thick emission from the photosphere and chromosphere

(2) optically thin emission from the corona

(3) optically thick emission from the wind

$$(R/R_{star})^2 T_B = T_{chr} + (1-e^{-\tau})(R_{cor}/R_{star})^2 T_{cor} + (R_{wind}/R_{star})^2 T_{wind}$$

Also, CO pure rotation lines and recombination lines.

Magnetic emission processes

- Gyroresonant emission: free-free emission from coronal thermal electrons at the cyclotron frequency and harmonics (s<10)
  > cyclotron frequency: ν_{cyclo}=0.0028B (GHz)
  > for 10^{th} harmonic: λ=1cm/B(kG)
- Nonthermal gyrosynchrotron emission (s>>10) but very small optical depths at mm wavelengths, except during flares.

Chromospheric magnetic fields II

- Gyroresonant emission: thermal coronal electrons emitting at $s\nu_B$ where $s<10$ ($s=3$ for optically thick emission from solar active regions at cm wavelengths)
- Cyclotron frequency: $\nu_B=0.0028B$ GHz
- At 1mm need B=35 kG for $s=3$ (not possible)
- At 1 cm need B=3.5 kG for $s=3$ (VLA not ALMA observations)
- For active stars (young, rapid rotators, dMe) with $T\geq10$ MK coronae, $s>3$ modes could be optically thick, so search for gyroresonant emission at mm wavelengths. If optically thick over whole star, then $T_B=T_{cor}\approx10^7$ K.

ALMA's planned capabilities
(all not yet available)

- Frequencies: 35-950 GHz bands (0.3-8.6 mm)
- Angular resolution: ~0".2(300/ν(GHz)(1km/baseline): now 5 mas for maximum baseline of 16 km.
- Spectral resolution: 7680 frequency channels, now R=10,000,000 or 30 m/s.
- Sensitivity: 2 minute exposure of α Cen A and B at 344 GHz (0.87 mm) gives S_ν=26 mJy with S/N=137. Angular diameter of α Cen A is 10 mas. Nearby M dwarfs have angular diameters of 1 mas.
- High cadence rate: <1 sec
- Polarization

Some useful equations for understanding ALMA data

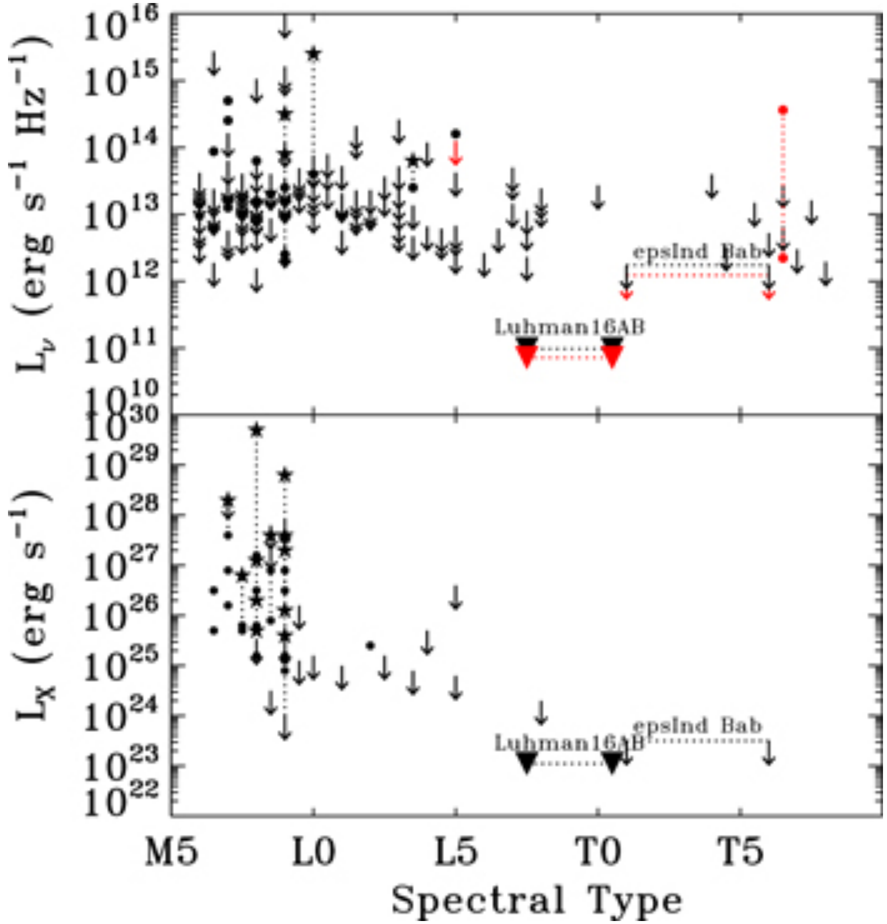
$$T_B\,(K)=254\ d(pc)^2 S_\nu(mJy)/(1mm/\lambda)^2(R/R_{sun})^2$$

$$S_\nu(mJy)=0.00394(1mm/\lambda)^2(R/R_{sun})^2 T_B/d(pc)^2$$

For more information see the ALMA Cycle 4 Technical Handbook.

Could ALMA detect brown dwarfs chromospheres?

- Late M and some early L stars are detected as X-ray sources and likely have chromospheres.
- Luhman 16AB (L7.5, T0.5) are closest brown dwarfs at 2.0 pc.
- $R \approx R_{Jup} \approx 0.1 R_{Sun}$
- Chromosphere flux seen by ALMA should be about 0.7% that of α Cen A. Should be feasible.



Osten et al. (ApJL 805, 1 (2015))

VLA observations of dMe stars (Leto et al. A&A 2000)

Table 3. Observed fluxes and 3σ upper limits (in mJy).

Star	Observed fluxes X (8.4 GHz)	U (15 GHz)	K (22 GHz)	Q (43 GHz)	Predicted flux[a] X (8.4 GHz)	$T_B(R/R_*)^2$ [b] (8.4 GHz)
GJ 65AB (UV Cet)	2.61±0.12	<0.70	<1.57	<0.95	0.14–0.39	$1.7\ 10^8$
GJ 644 (V1054 Oph)	1.39±0.06	<0.87	<1.53	<1.40	0.53–1.30	$3.1\ 10^7$
GJ 752A (V1428 Aql)	<0.14	<0.64	<1.27	<1.10	0.007	$<8.3\ 10^6$
GJ 752B (V1298 Aql)	"	"	"	"	0.001	$<9.7\ 10^7$
GJ 803 (AU Mic)	<0.22	<0.92	<1.75	<1.30	2.74–9.50	$<3.2\ 10^7$
GJ 873 (EV Lac)	0.63±0.11	<0.78	<1.24	<1.10	0.75–1.08	$3.0\ 10^7$

[a] From the range of X-ray luminosities, using the emipirical relation by Güdel et al. (1993) (see Sect. 5).
[b] R/R_* is the radius of the emitting region computed from the minimum X-ray flux. It is of the order of 1 (see Benz et al. 1998).

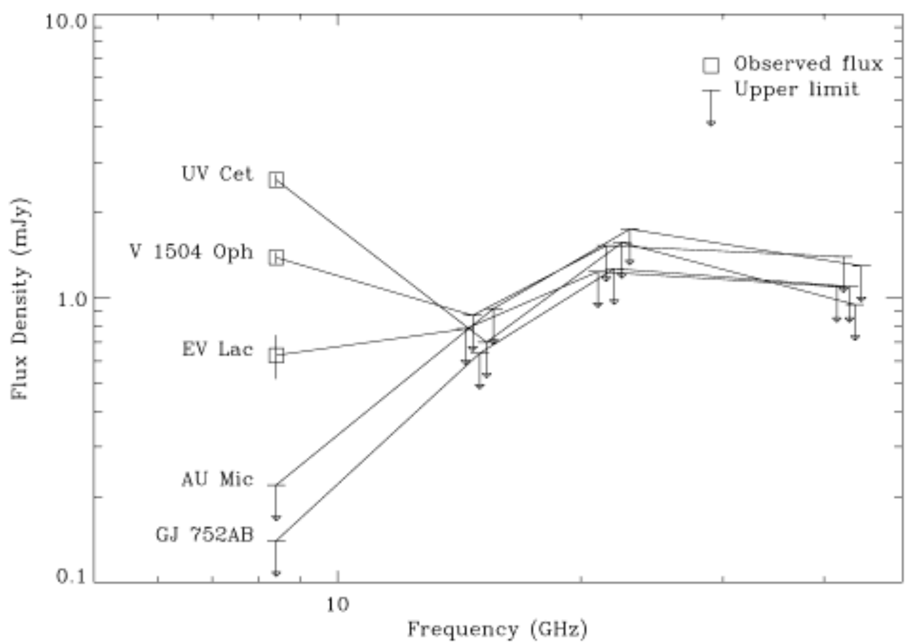
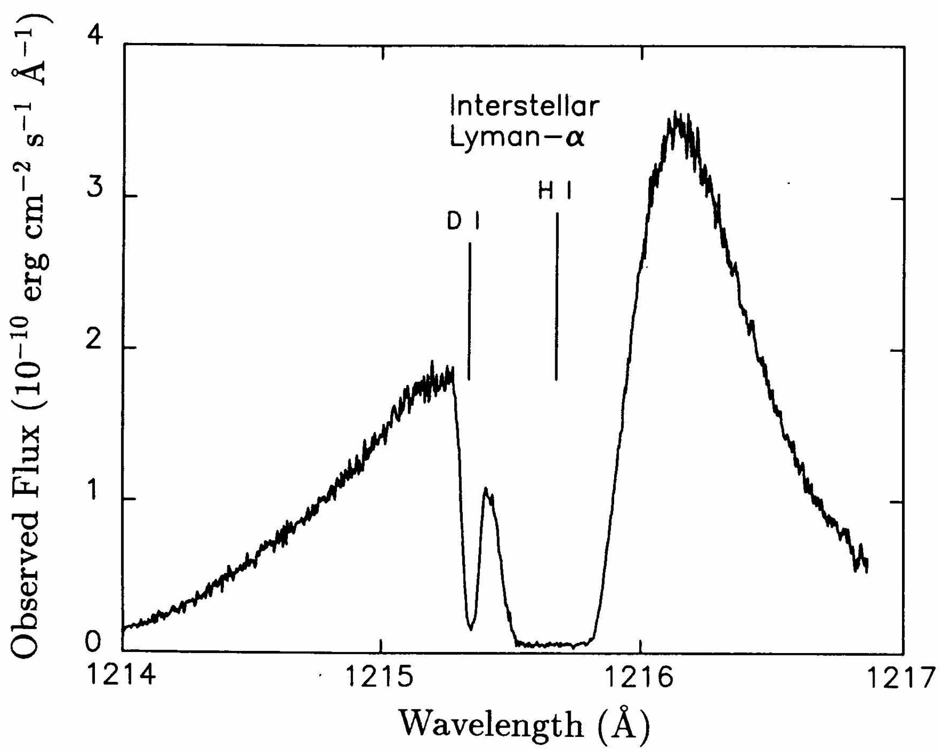


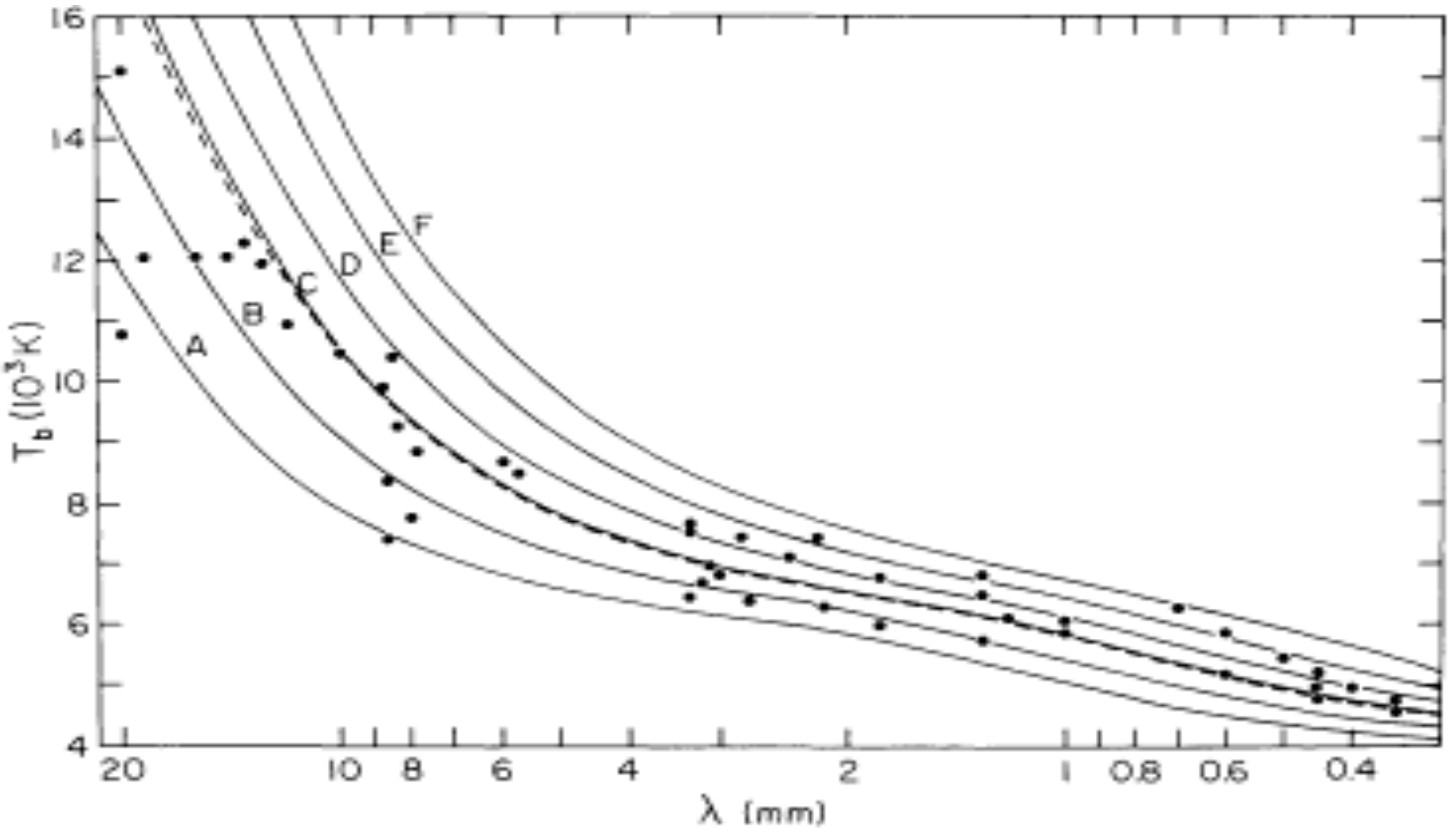
Fig. 1. Measured fluxes densities and upper limits versus frequency. The data at 15, 22, and 43 GHz are plotted with slight x-axis shifts for the sake of clarity.

The effects of interstellar H and D Lyman-α absorption on a stellar emission line

- The D Lyman lines are Δv= -82 km/s relative to H.
- $\tau_0(H)=66{,}700\tau_0(D)$
- Analysis is complicated due to uncertain intrinsic profile, flat curve of growth for H, multiple ISM velocity components.
- log N(HI)=18.24 to Capella
- Profiles of FeII and MgII lines contain important ISM velocity information.
- High resolution required (3 km/s very useful – HST/STIS).
- To measure D/H, FUSE was needed to go beyond the Lyα horizon (log N(HI)=18.7) using higher Lyman series lines.

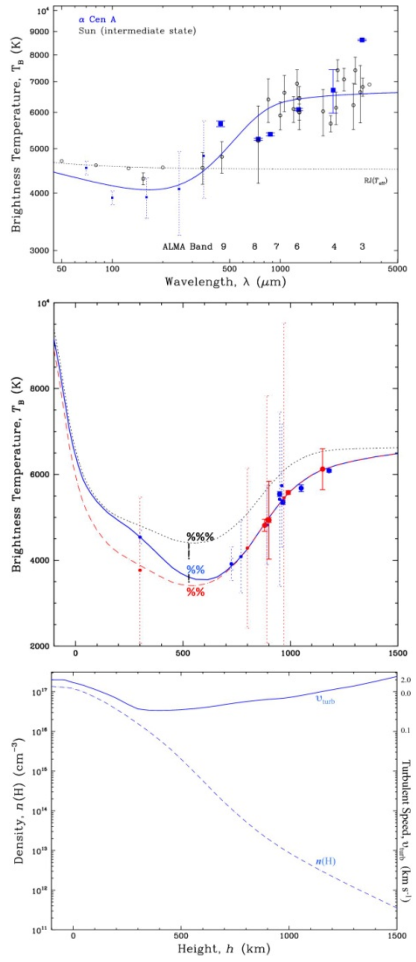


Comparison of solar observations with VAL (1981) model predictions as f(λ)



Comparison of ALMA brightness temperatures with chromospheric models

- Top: Blue line is a solar chromospheric model (based on UV flux and emission lines) with T_{min}=3800 K.
- Observed brightness temperatures predict T_{min}=3550 K.
- ALMA is observing other nearby stars with increasing accuracy and precision.



What aspects of the solar-stellar connection can ALMA address?

- Thermal structure and heating rates of stellar chromospheres.
- Spatial and temporal variability of chromospheres.
- Do A and B stars have chromospheres?
- Do brown dwarfs have chromospheres?
- Chromospheric magnetic fields.
- Flares (heating and beams).

How could new observing capabilities permit us to better understand the solar-stellar connection?

> Measure the thermal structure of stellar chromospheres

-- test models based on UV spectroscopy

-- precise location and amount of non-radiative heating

> Determine the limits of stars in the HR Diagram where solar-type phenomena disappear (hot coronae, X-rays, gyrosynchrotron radio emission, chromospheres, flares, etc.): OAB stars, late-M and brown dwarfs?

> Spatial inhomogeneity (active regions and starspots) and temporal variability of chromospheres

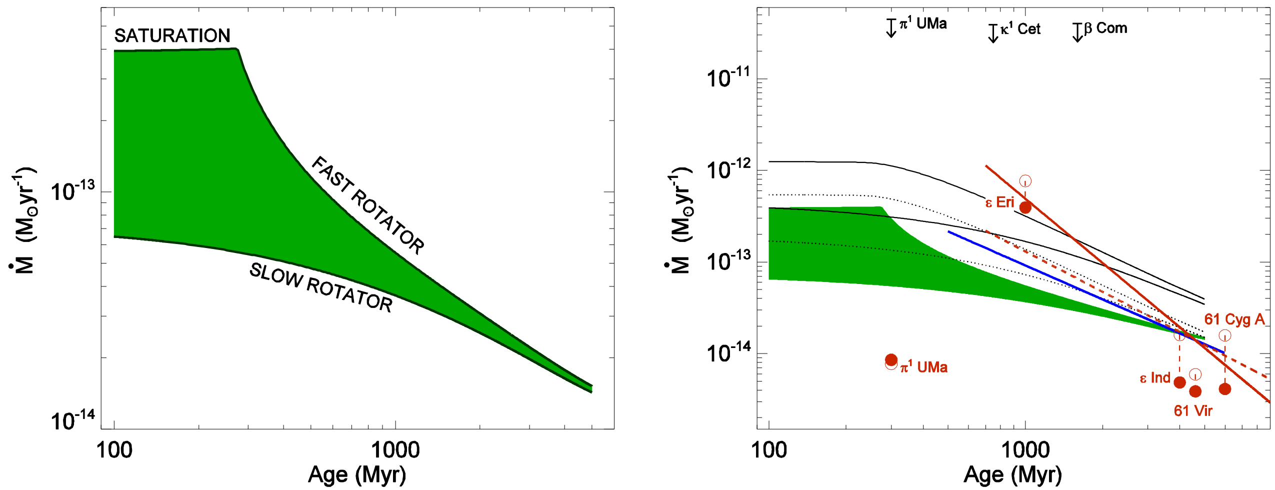
> Heating of chromospheres and photospheres during flares

> Mass-loss rates for giants but unlikely for dwarfs

> Measure magnetic fields in chromosphere from circular polarization of free-free emission

- The unexpected.

Can ALMA measure stellar mass-loss rates? For optically thick free-free emission from winds, mass-loss rate $dM/dt \sim \nu^{-1}$ (Wright&Barlow 1975)



Green area shows model of Johnstone et al. (2015) for G and K dwarf stars with initially fast or slow rotation. Red line and points show mass-loss rates using the astrosphere method (Wood et al. 2005,14). VLA upper limits from Gaidos et al. (2000). Optically thick wind emission more easily seen by ALMA than VLA because much less gyrosynchrotron emission at mm wavelengths and weaker free-free emission from lower in chromosphere, T_B(mm)<T_B(cm) . ALMA will detect winds of luminous stars.