Image credit: Invader Xan

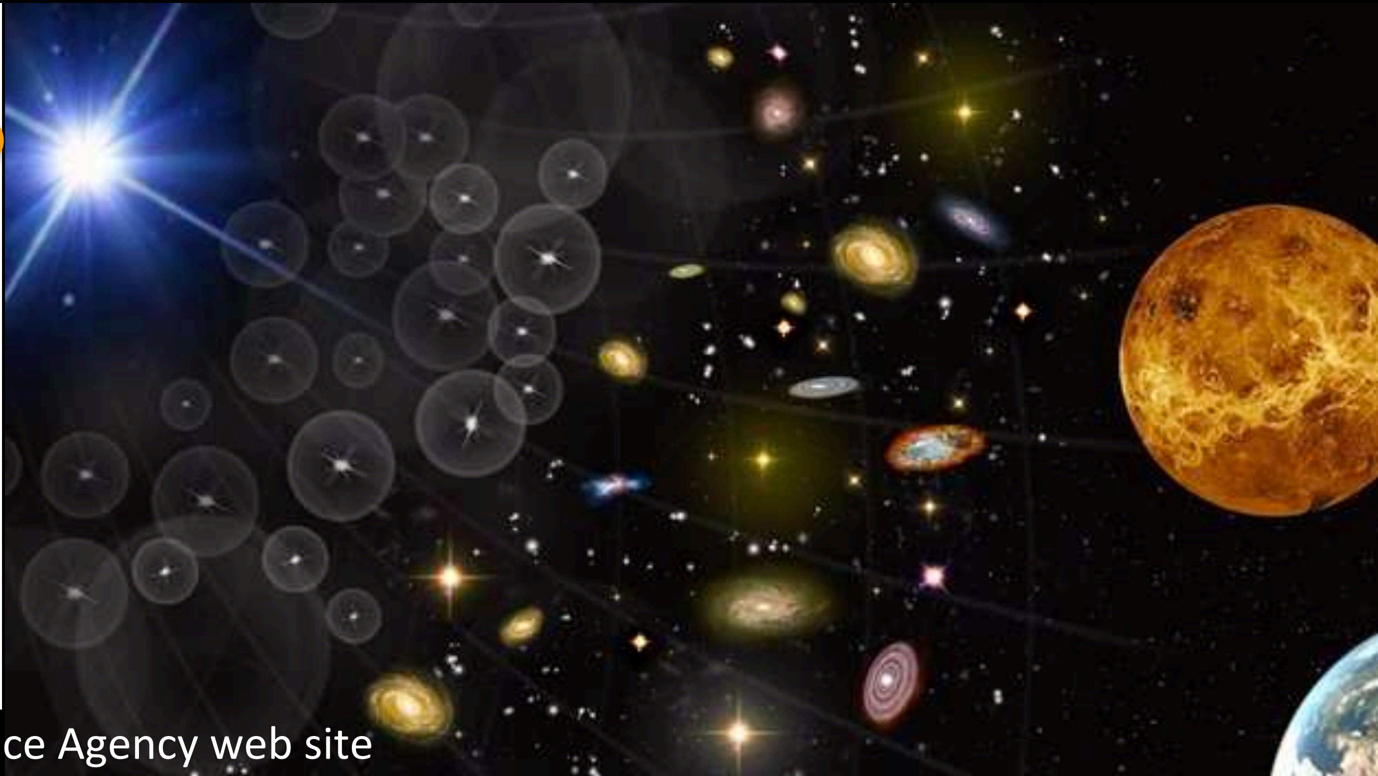
VLBI of stellar and sub-stellar magnetic activity

Jackie Villadsen, NRAO Charlottesville

How does (sub)stellar magnetic activity relate to astronomy's big questions?

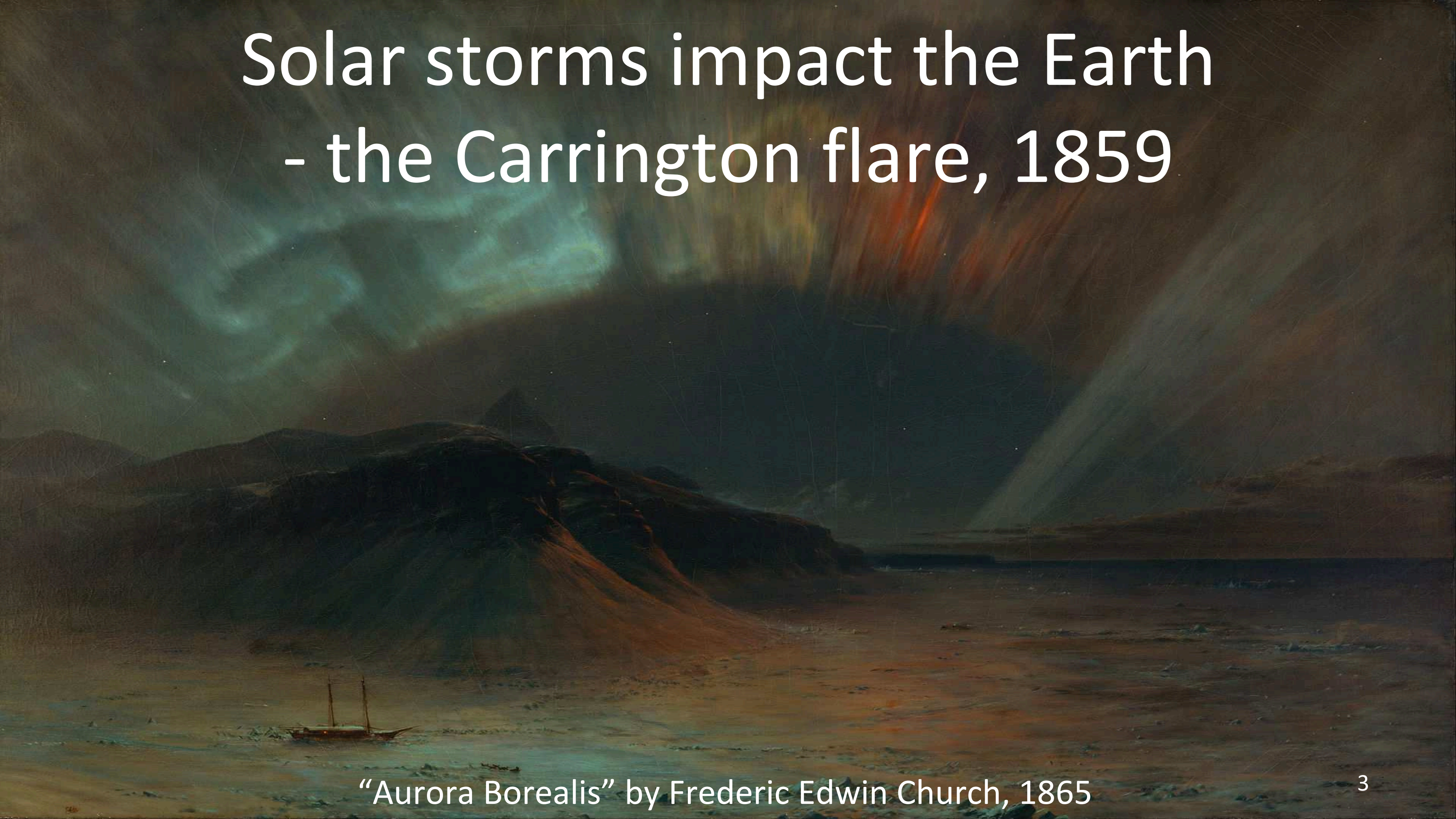
Cosmic Vision themes

- The Hot and Energetic Universe
- The Gravitational Universe
- Planets and Life
- The Solar System
- Fundamental Laws
- The Universe



Images from European Space Agency web site

Solar storms impact the Earth - the Carrington flare, 1859



“Aurora Borealis” by Frederic Edwin Church, 1865

"Space weather": how stellar magnetic activity impacts the planet's atmosphere

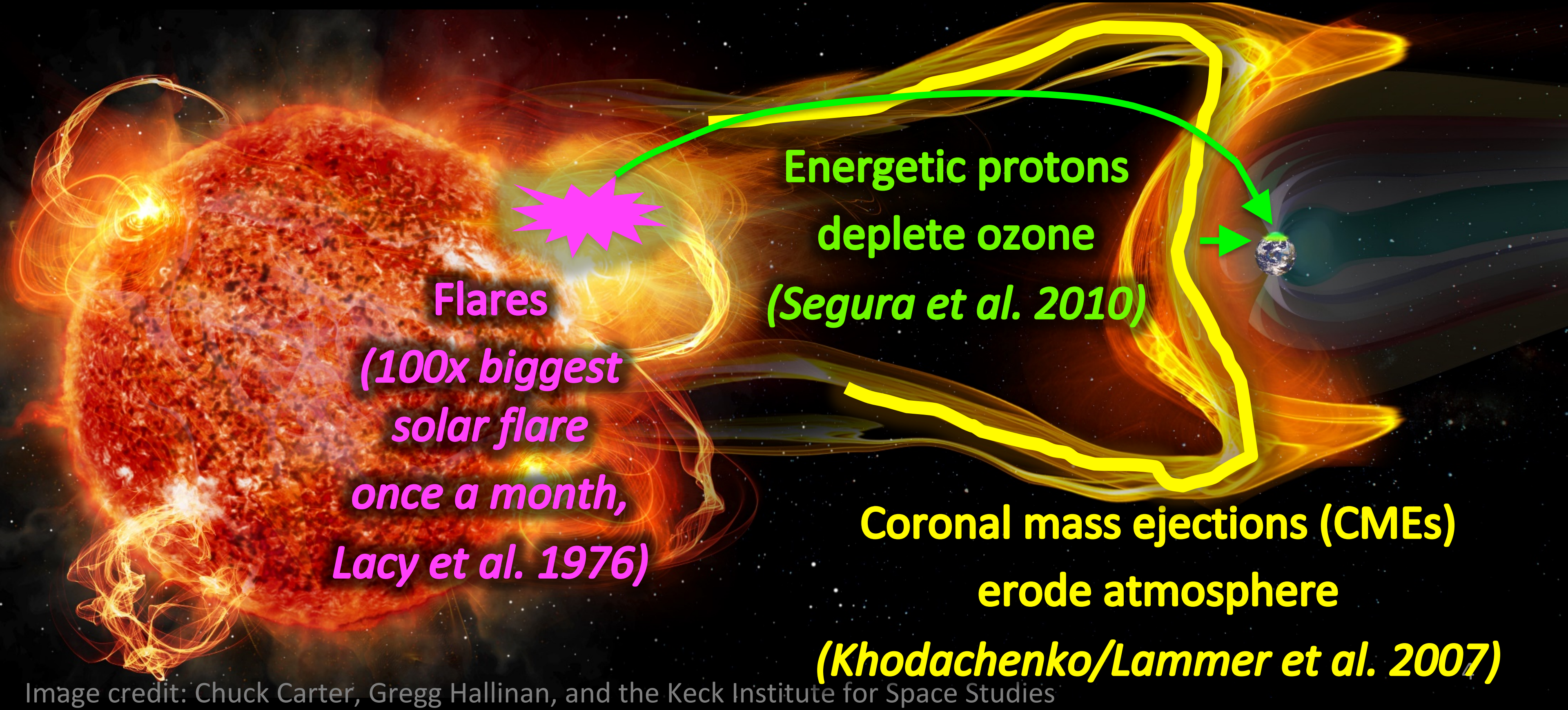


Image credit: Chuck Carter, Gregg Hallinan, and the Keck Institute for Space Studies

“Space weather”: how stellar magnetic activity impacts the planet’s atmosphere

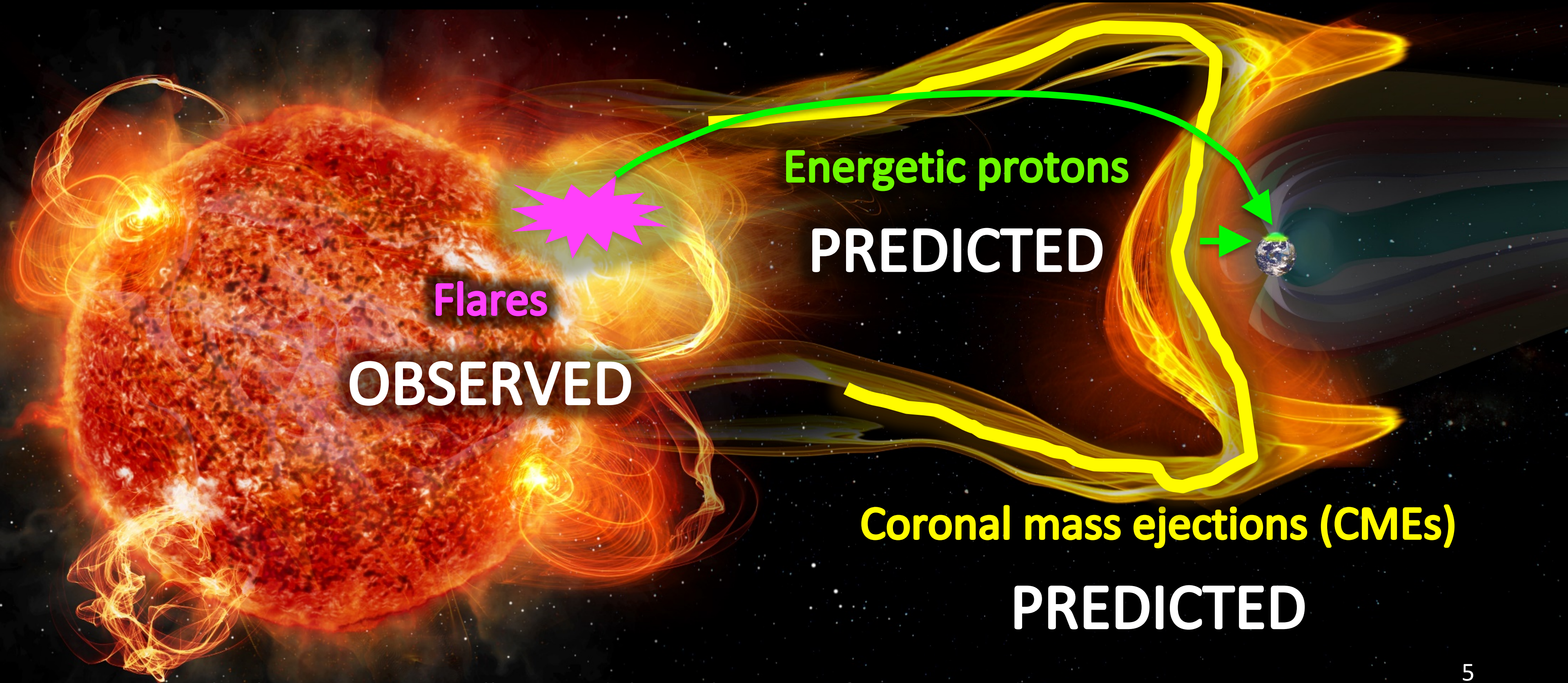
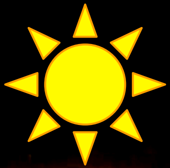
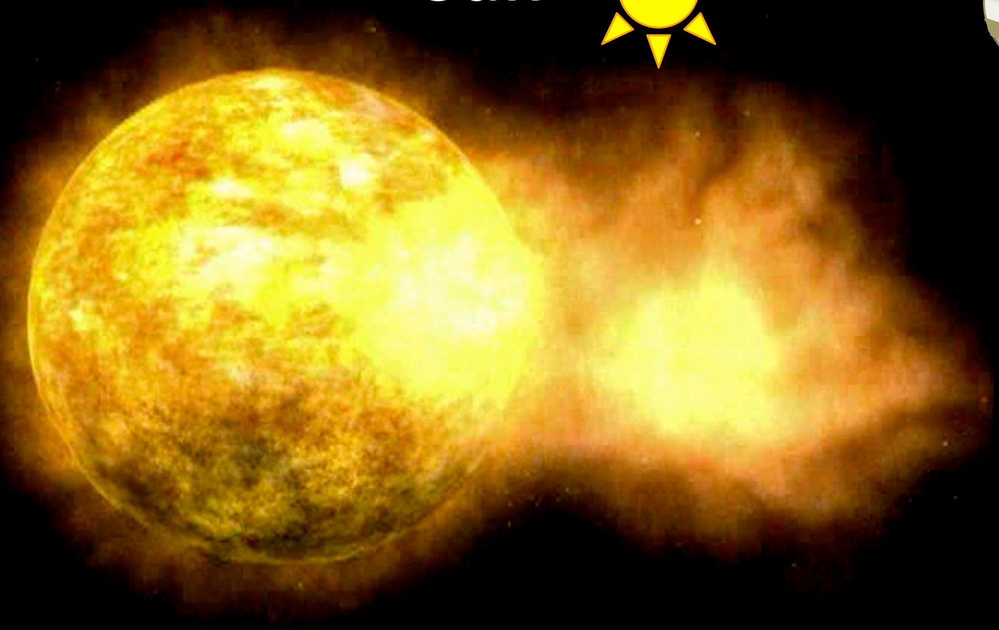


Image credit: Chuck Carter, Gregg Hallinan, and the Keck Institute for Space Studies

Predictions of extrasolar space weather use solar system templates

Sun





Planets

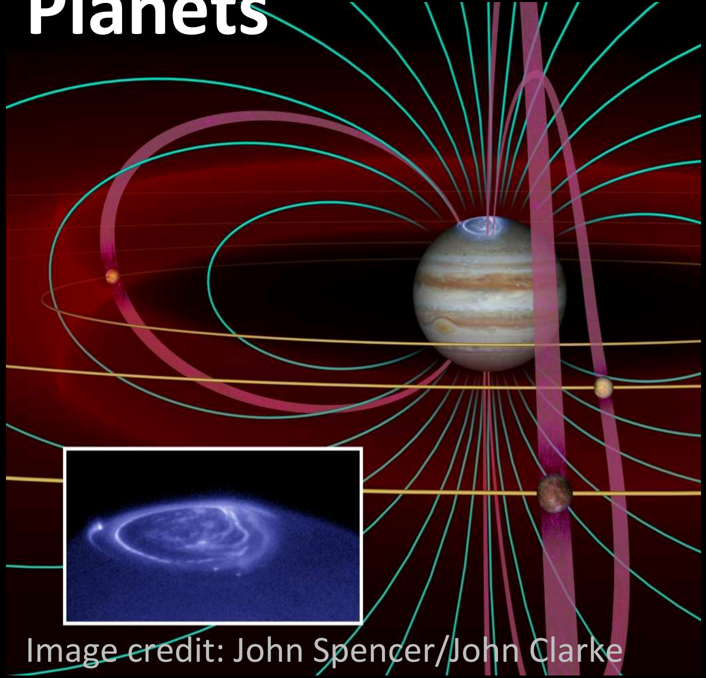
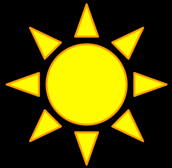


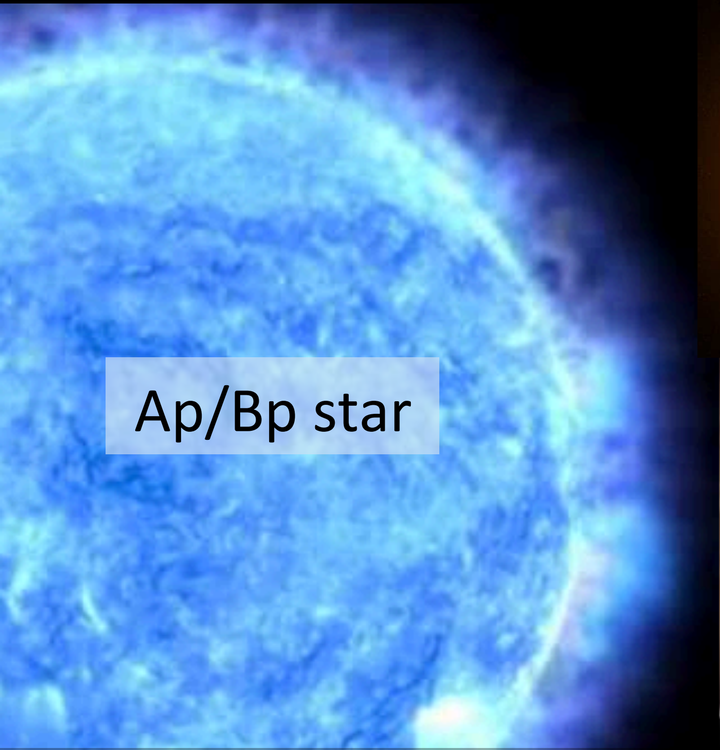
Image credit: John Spencer/John Clarke

Flares Hot corona Wind/CMEs

Aurorae Moons Radiation belts

We need both templates to understand magnetic activity on diverse types of stars





Young Sun

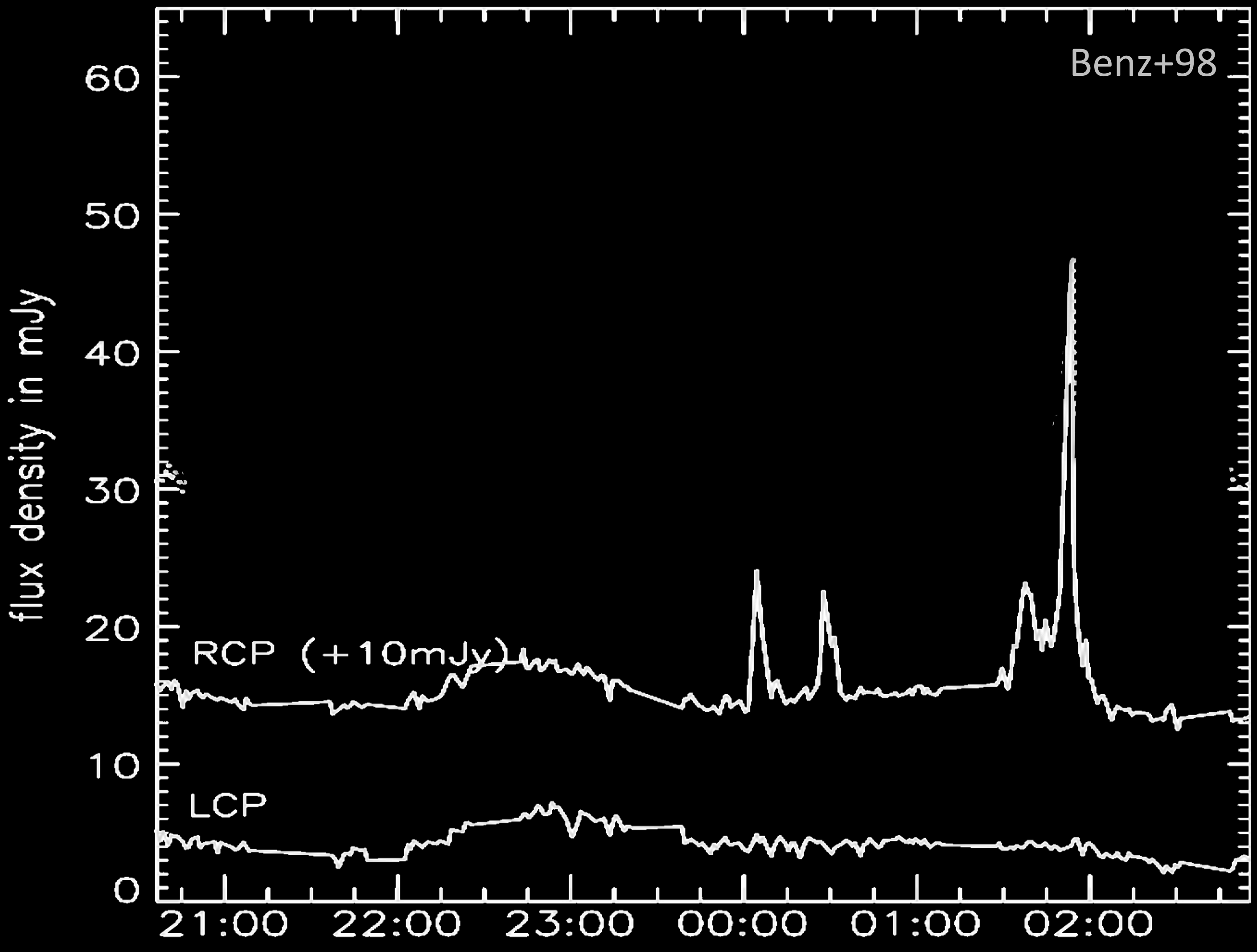
Red dwarf

Image credits: rvcj.com (B star), earth-chronicles.com (young Sun), sciencepart.com (red dwarf), Bob King (Algol)

How does radio emission trace (sub)stellar magnetic activity?

Active stars produce bright radio emission at GHz frequencies:

Example: UV Ceti, a young M dwarf

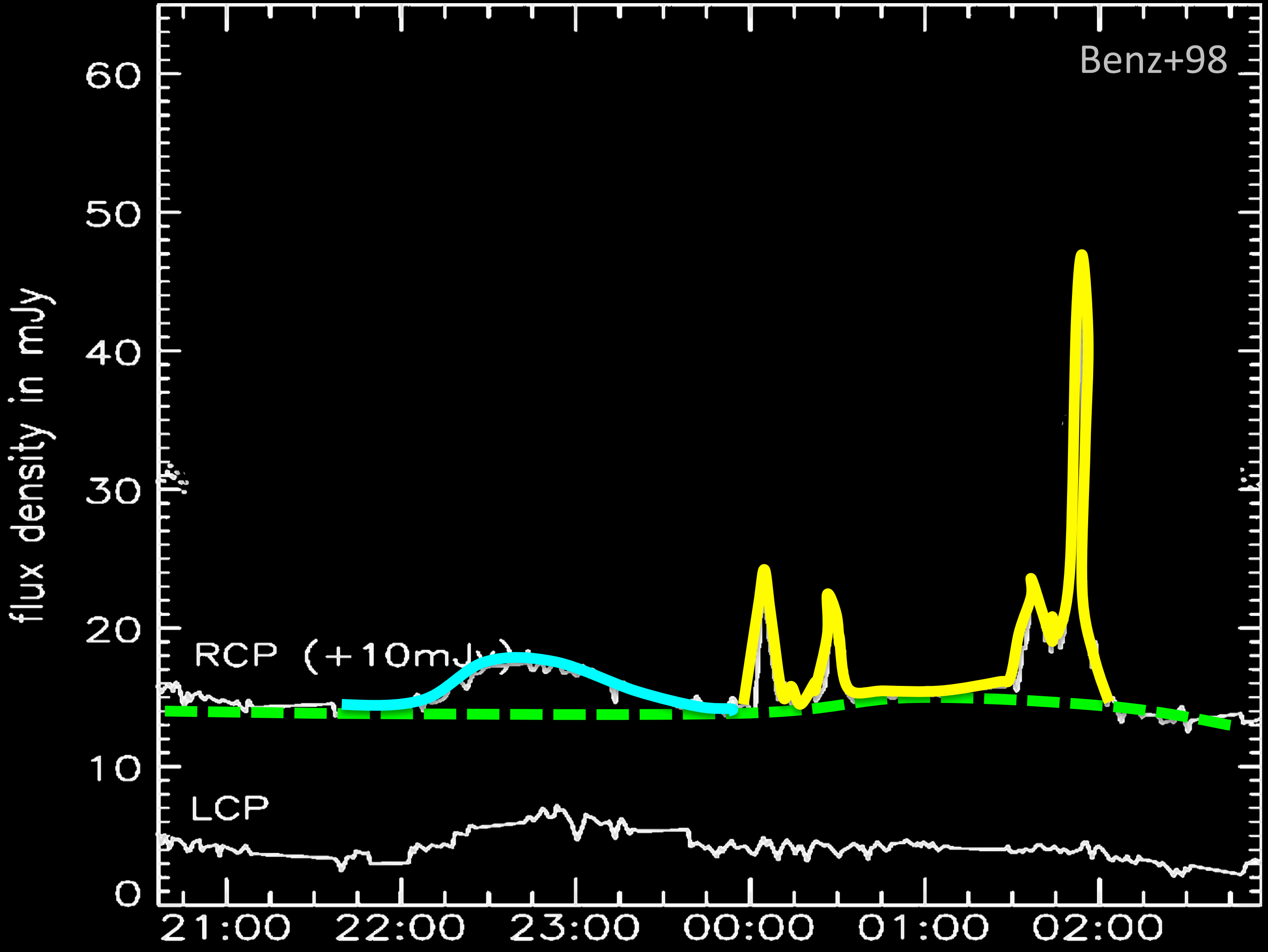


Active stars produce bright radio emission at GHz frequencies:

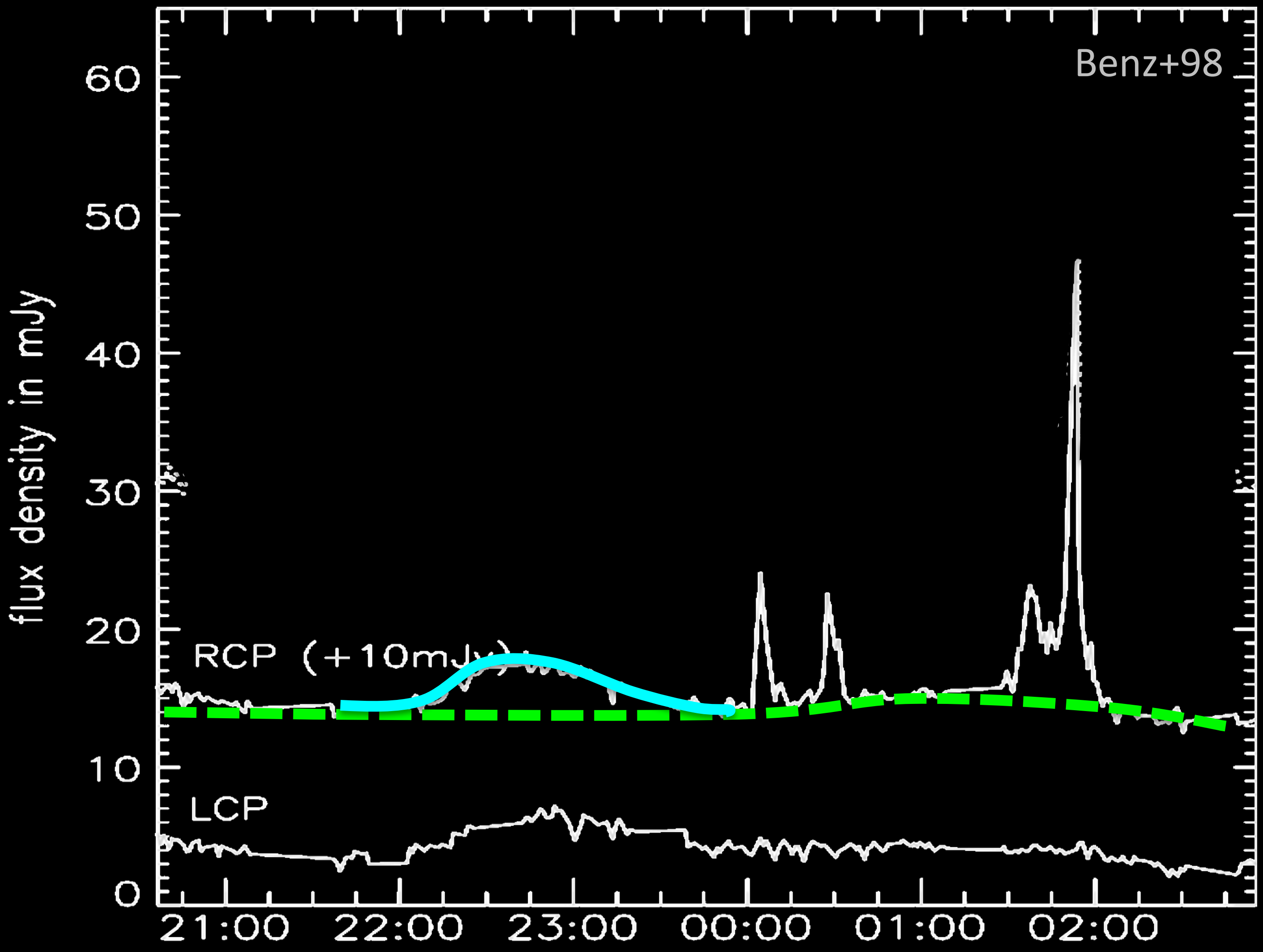
quiescent emission

incoherent flares

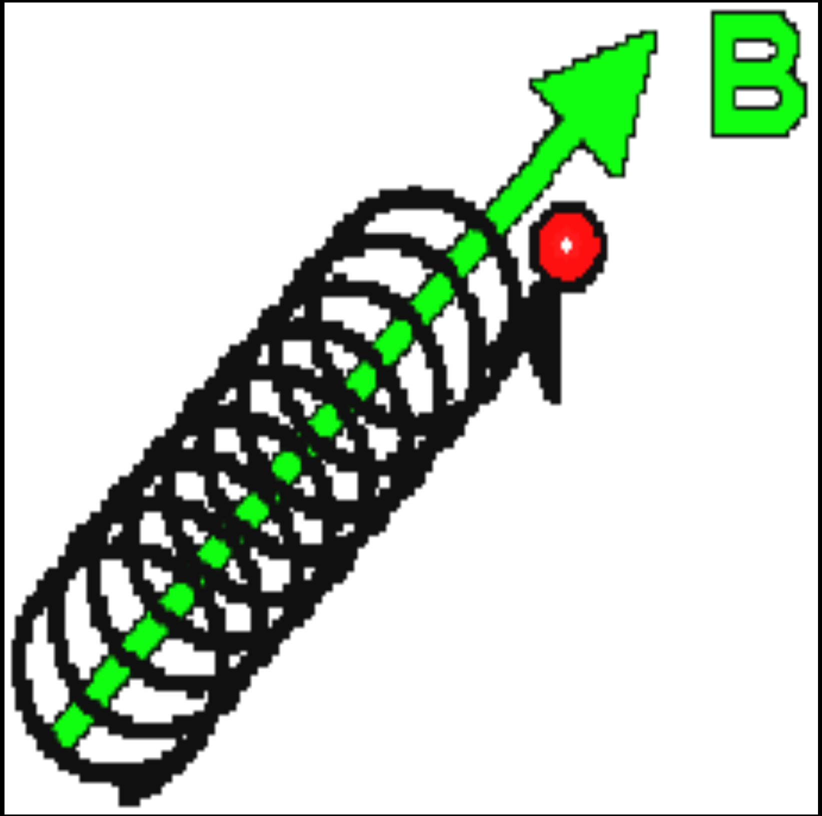
coherent bursts



Quiescent emission and incoherent flares are attributed to <u>gyro-synchrotron</u> from mildly relativistic electrons



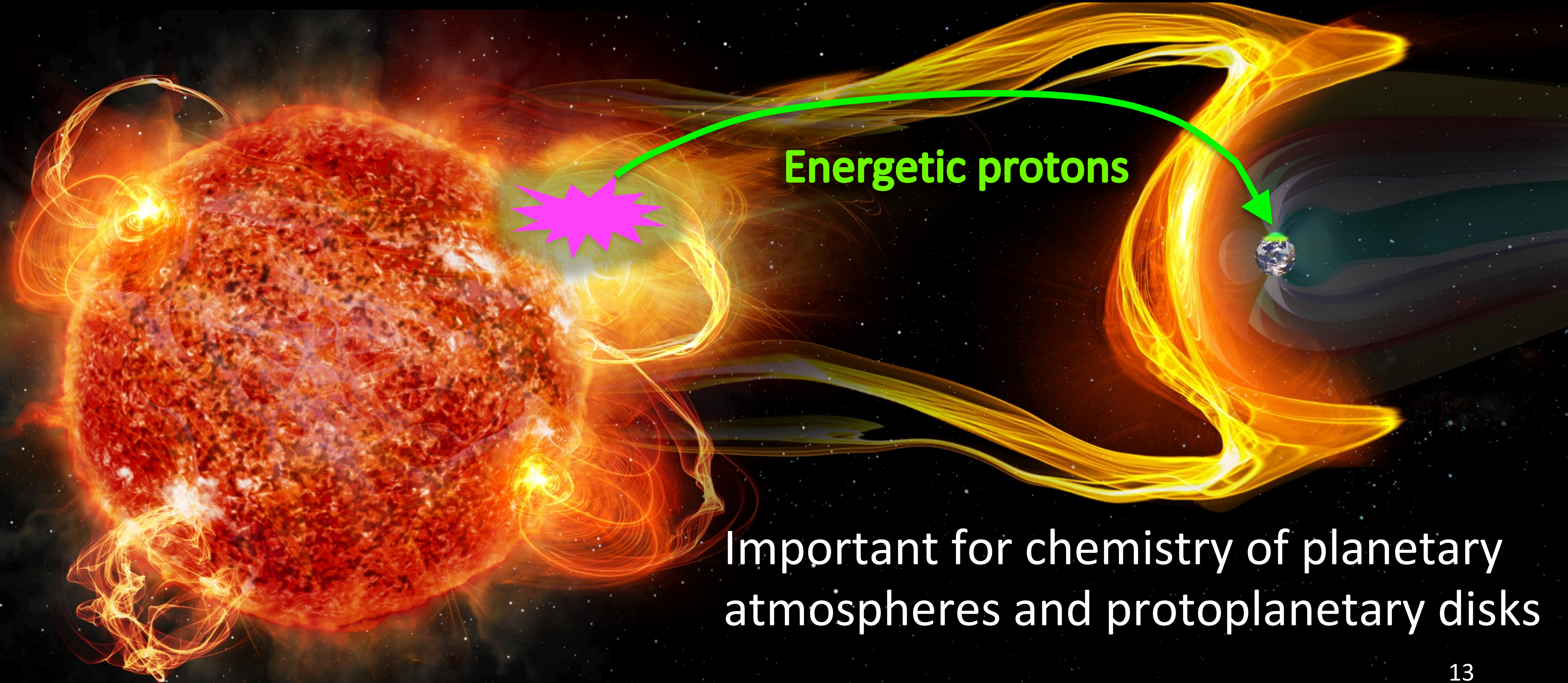
Gyrosynchrotron originates directly from energetic electrons spiraling around magnetic field lines



http://tempest.das.ucdavis.edu/pdg/ECE/

→ Radio emission provides the only direct observation of energetic particles in stellar atmospheres.

Non-thermal radio emission can constrain energetic particle properties for extrasolar space weather



Important for chemistry of planetary atmospheres and protoplanetary disks

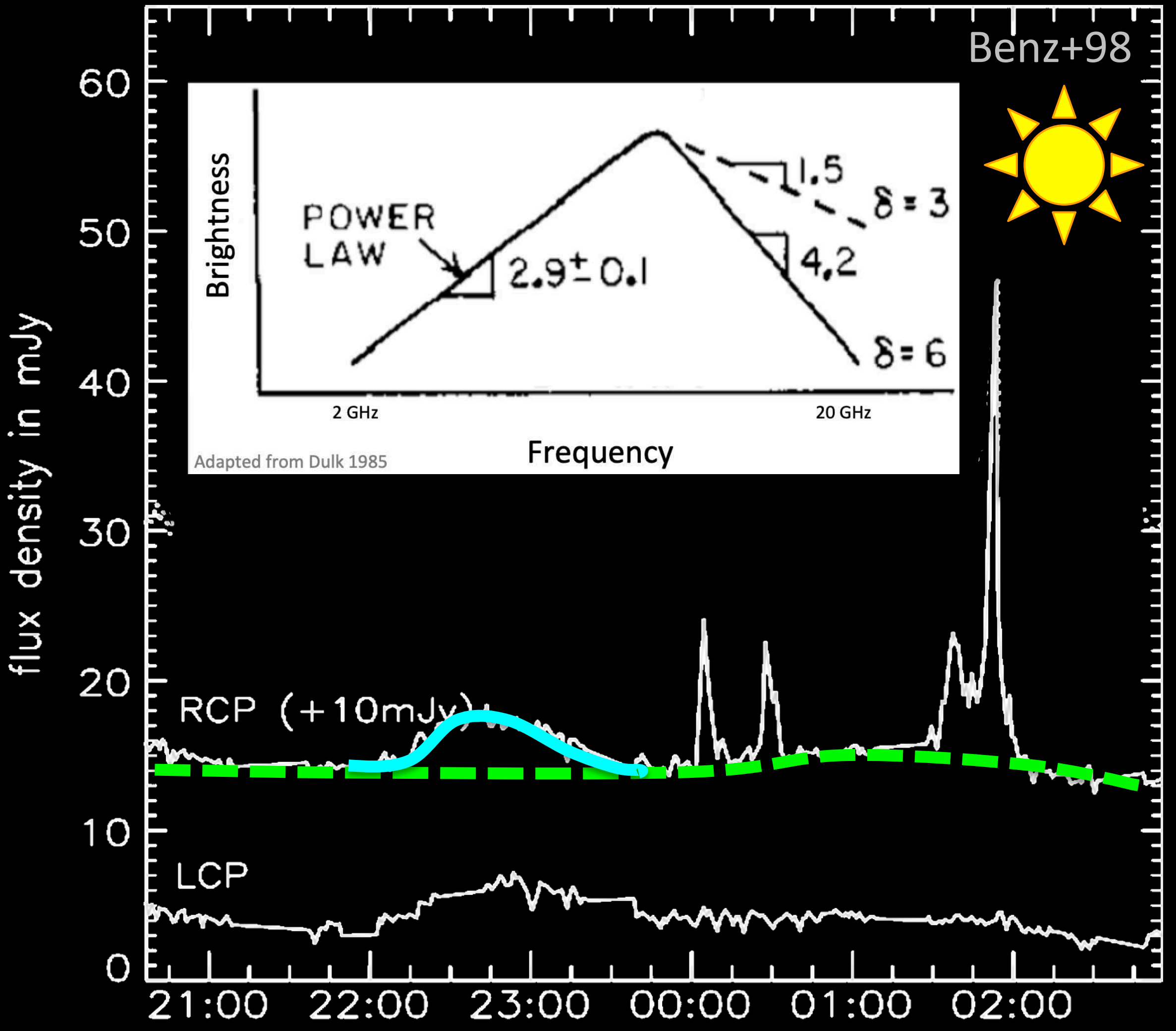
Image credit: Chuck Carter, Gregg Hallinan, and the Keck Institute for Space Studies

Why use VLBI to measure gyrosynchrotron source size and position?

The radio light curve and spectrum depend on:

- Energetic electron number density
- Electron energy distribution
- Magnetic field strength
- Source size

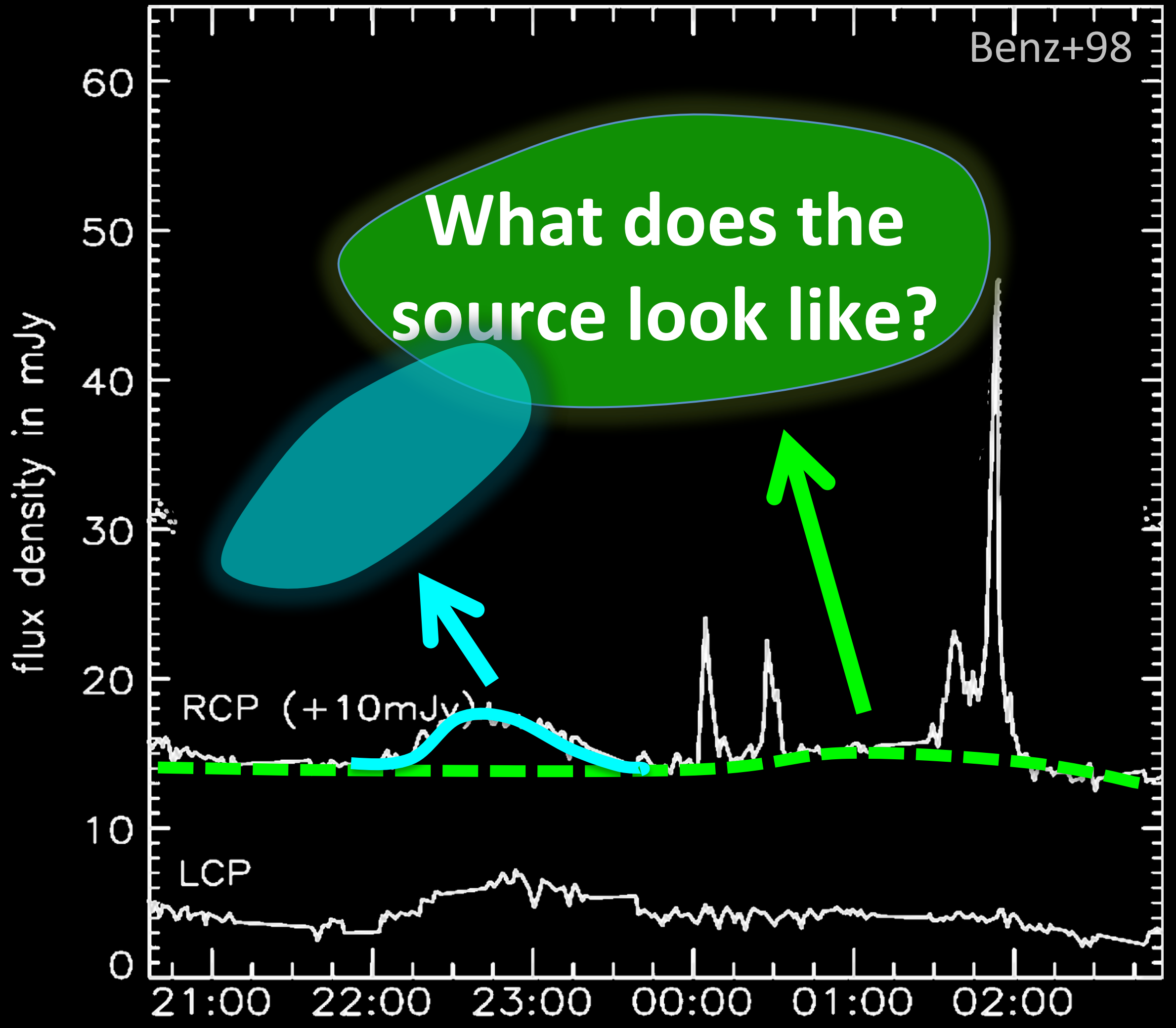
These properties are degenerate.



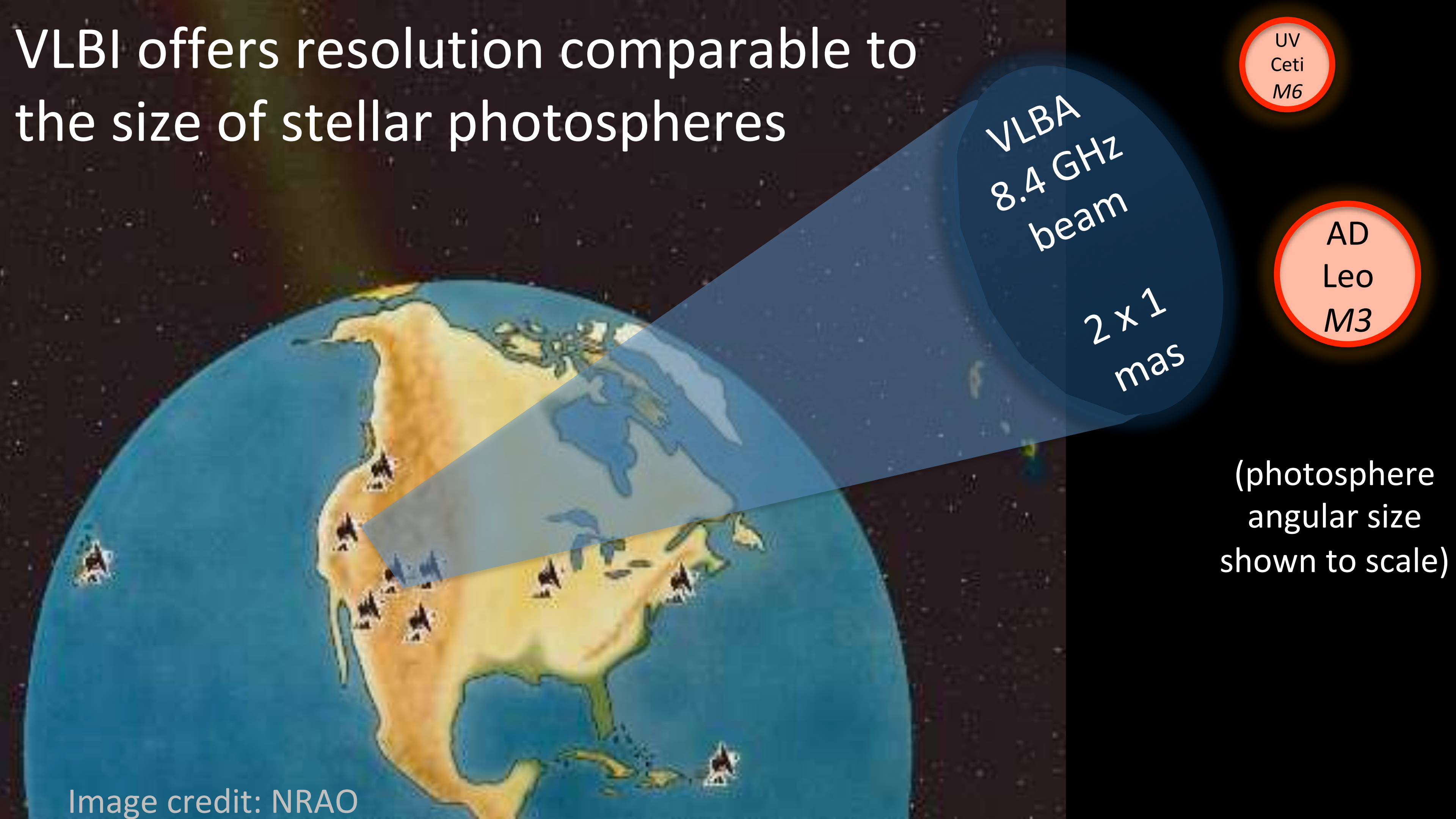
The radio light curve and spectral index depend on:

- Energetic electron number density
- Electron energy distribution
- Magnetic field strength
- Source size

These properties are degenerate.



VLBI offers resolution comparable to the size of stellar photospheres



The radio light curve and spectral index depend on:

- Energetic electron number density
- Electron energy distribution
- Magnetic field strength
- Source size ✓

These properties are degenerate.

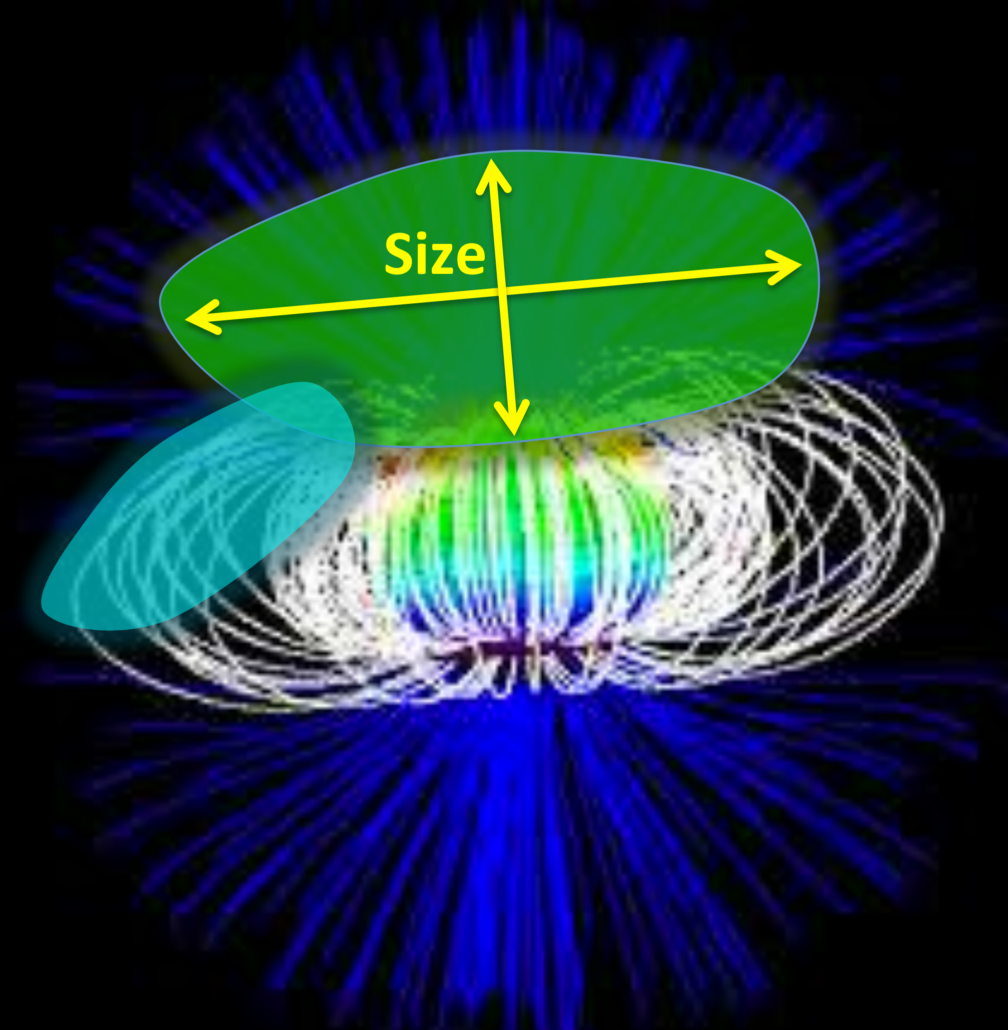
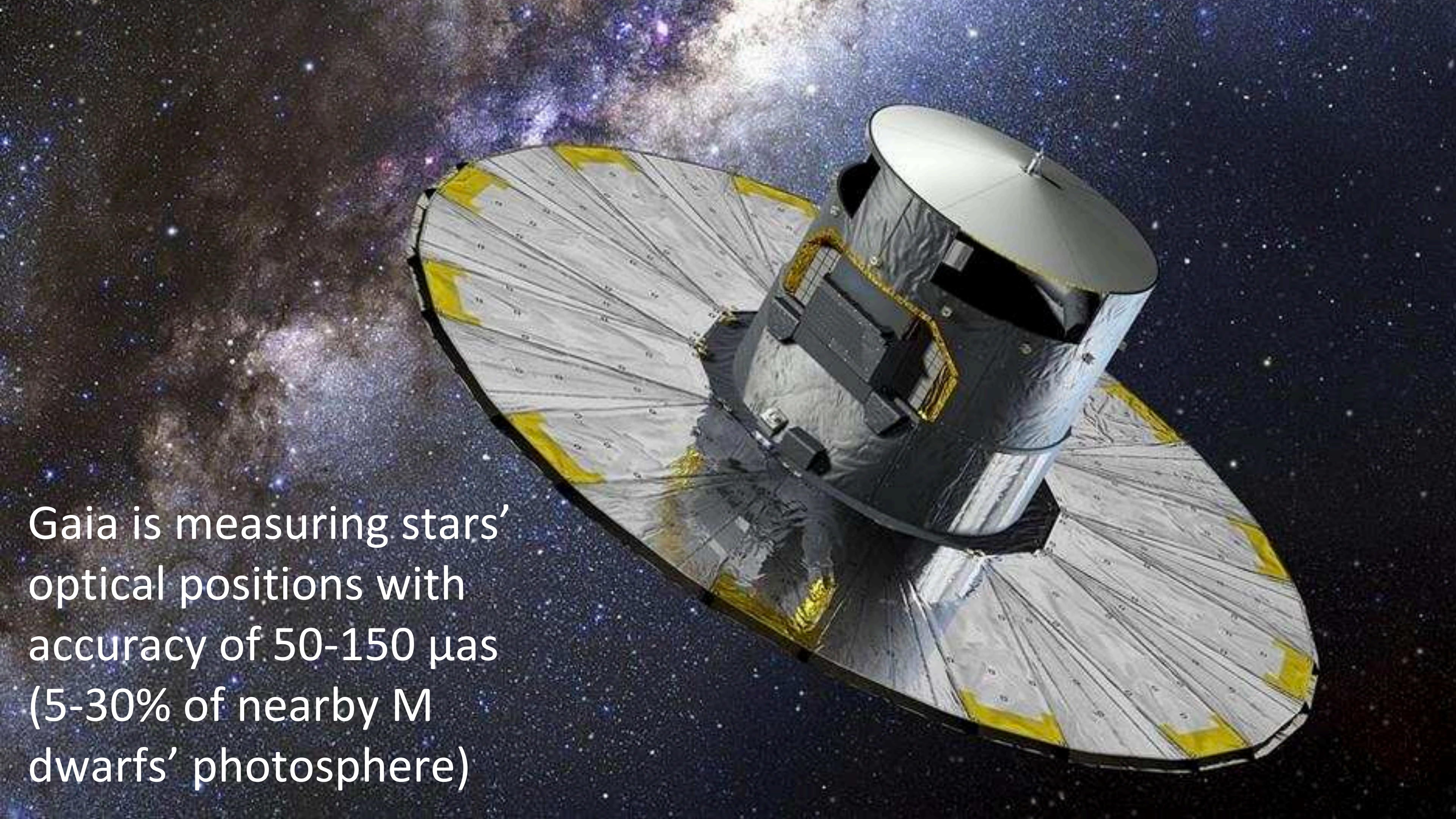


Image credit: Jardine & Donati


Gaia is measuring stars' optical positions with accuracy of 50-150 μas (5-30% of nearby M dwarfs' photosphere)

The radio light curve and spectral index depend on:

- Energetic electron number density
- Electron energy distribution
- Magnetic field strength ✓
- Source size ✓

~~These properties are degenerate.~~

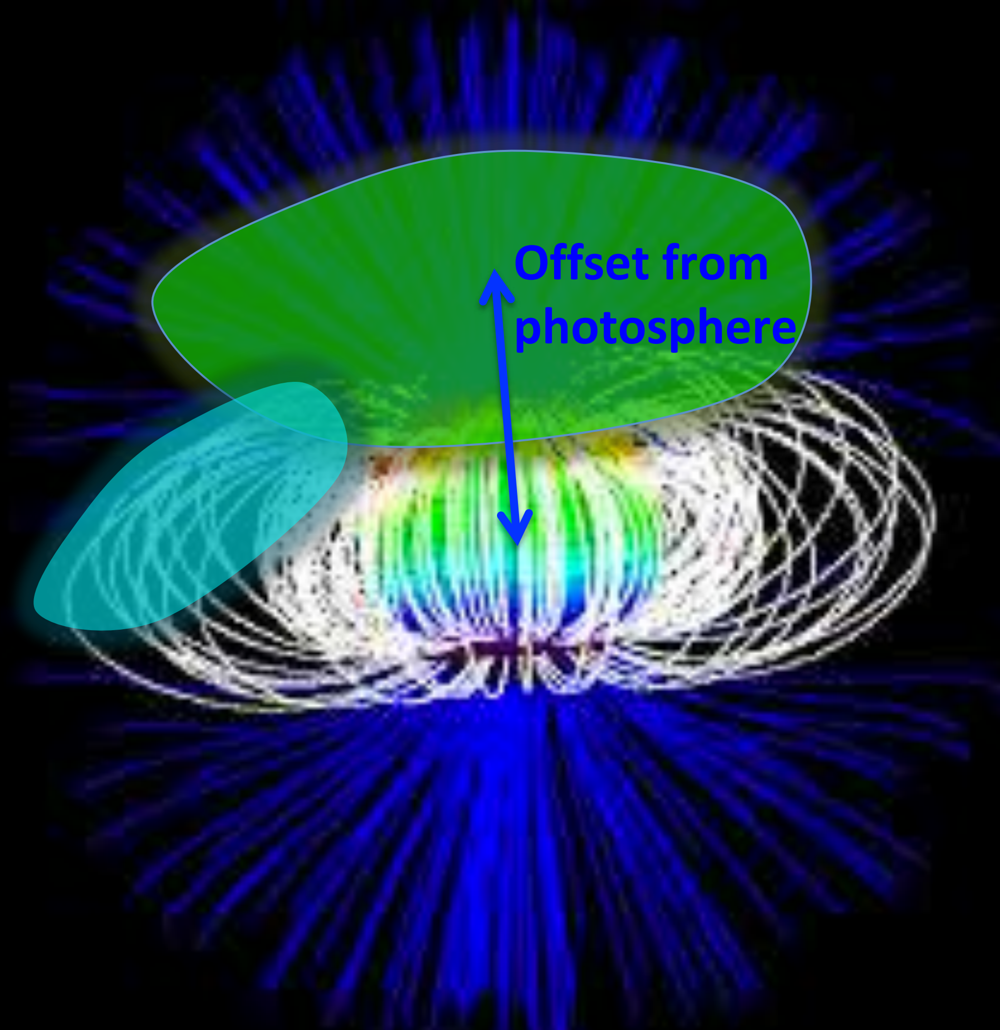
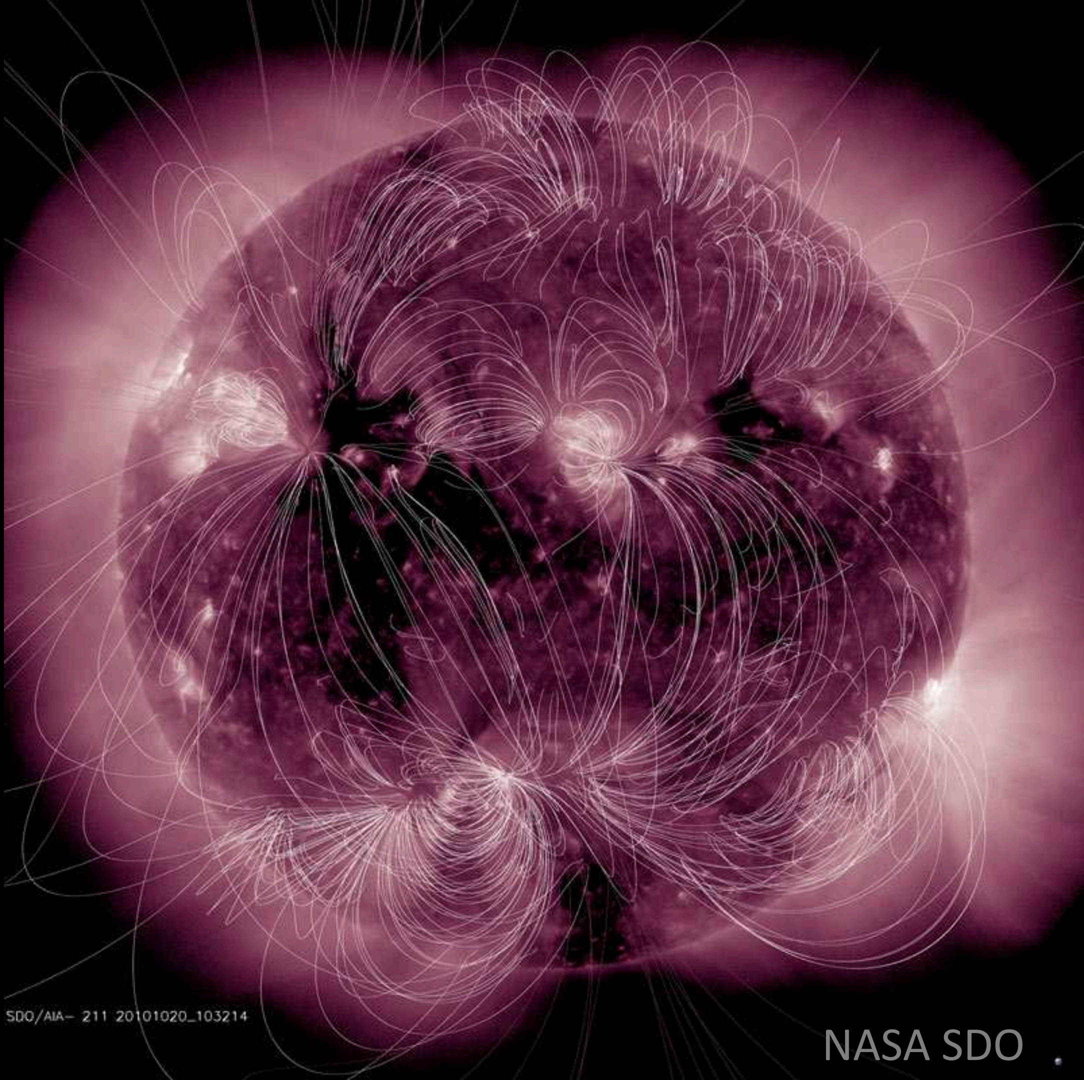


Image credit: Jardine & Donati

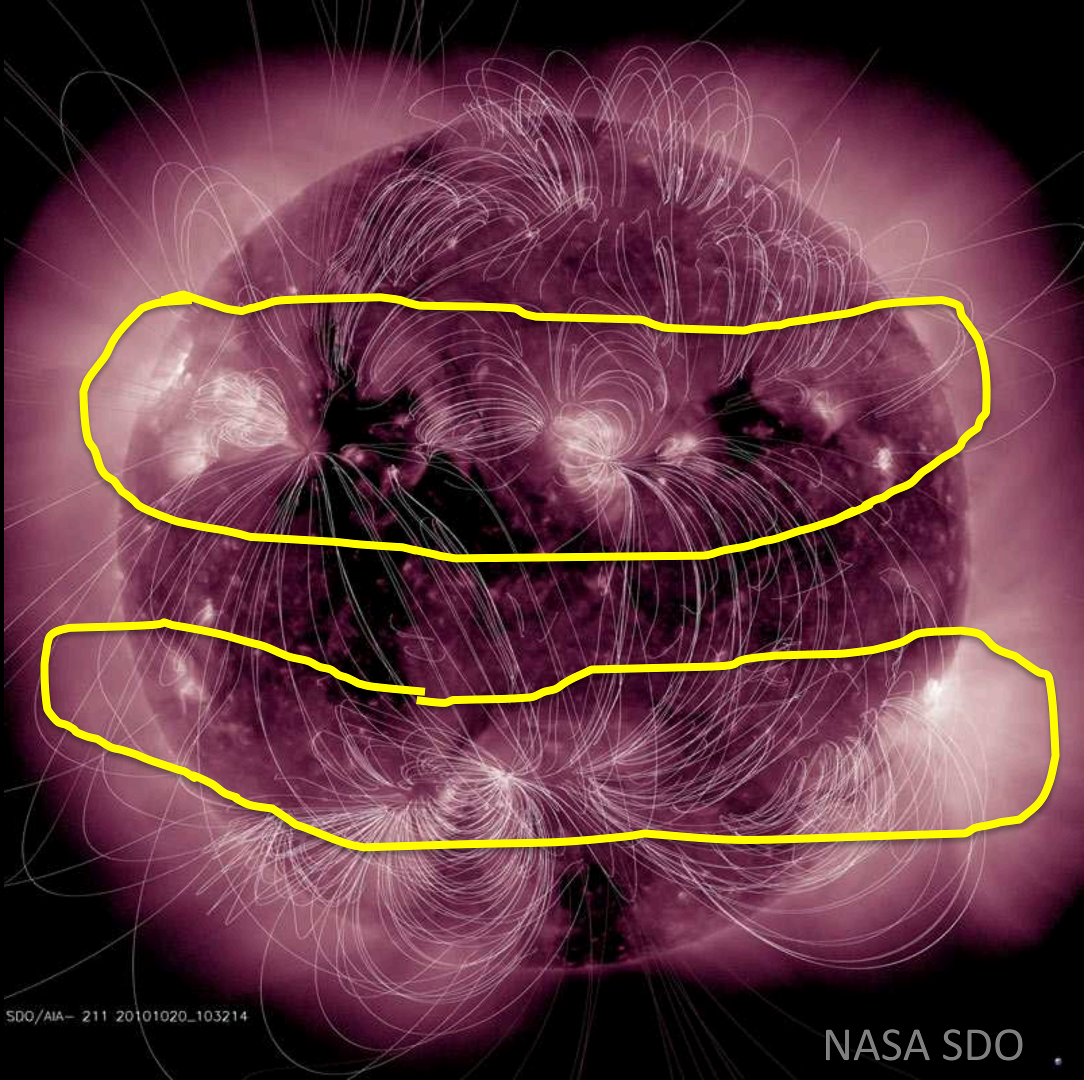
What determines the size of stellar magnetic structures and radio sources?

The solar corona is 1 million Kelvin plasma, confined by the Sun’s magnetic field



NASA SDO

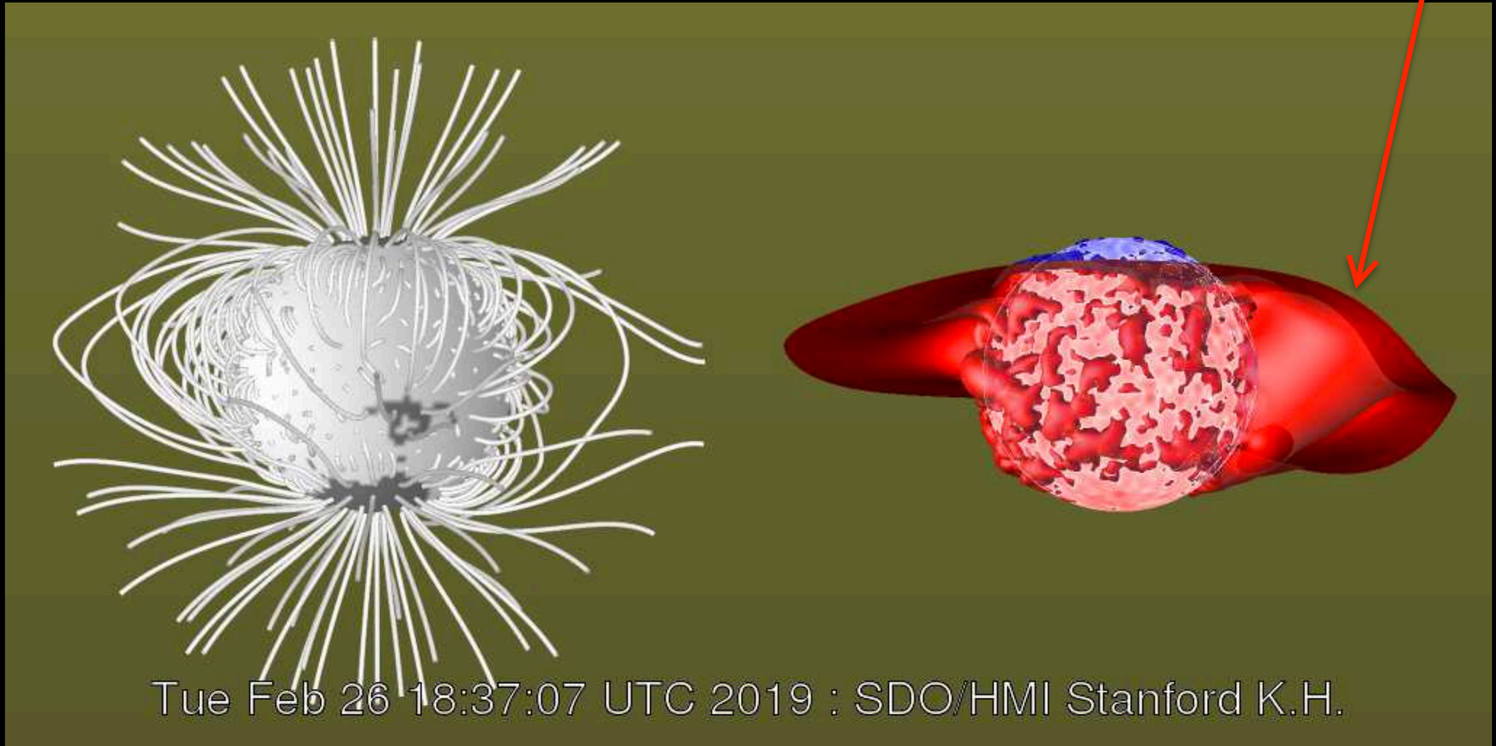
Most solar flares happen in small-scale magnetic loops above and below the equator



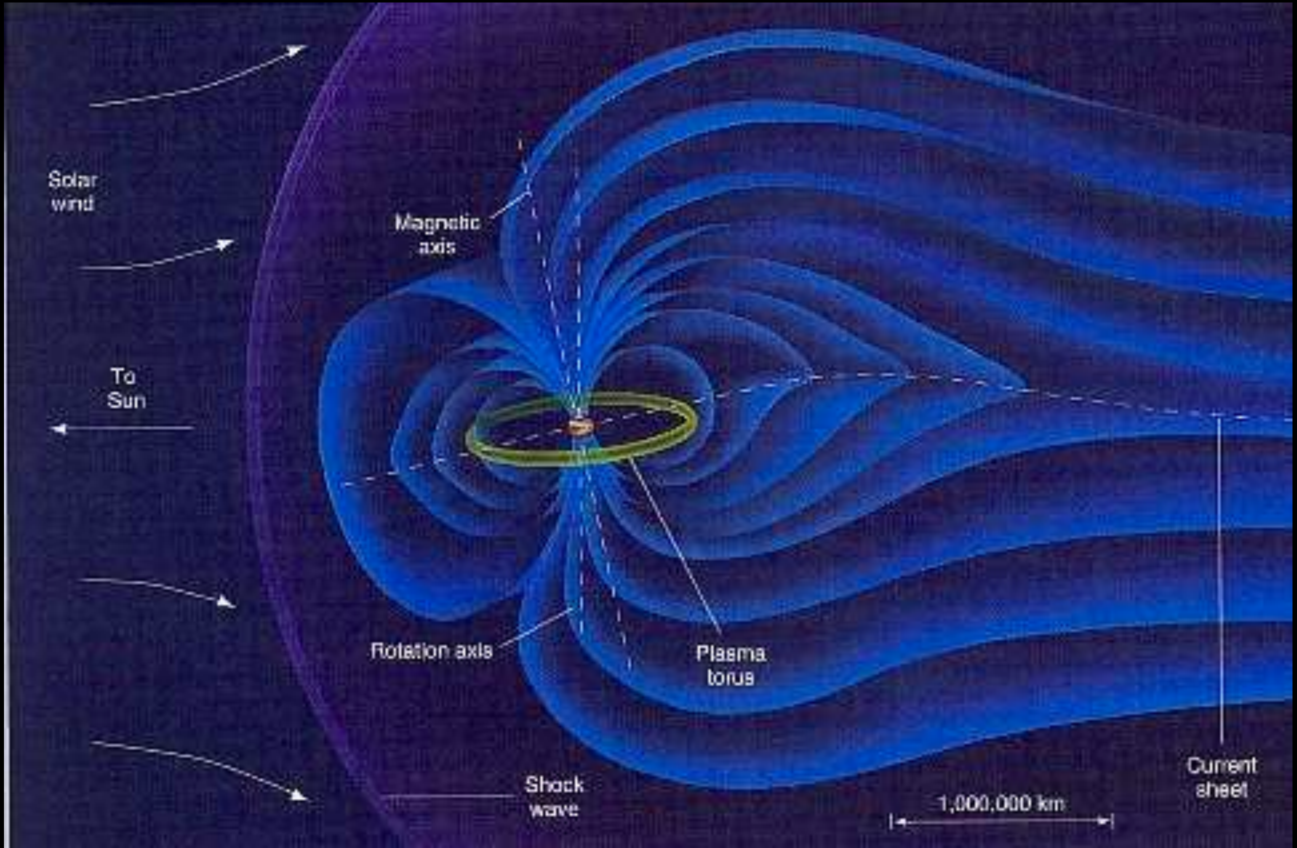
NASA SDO

The Sun’s closed magnetic field is <~2x size of Sun, due to balance between magnetic pressure and solar wind pressure

$$P_{wind} \sim P_{mag}$$

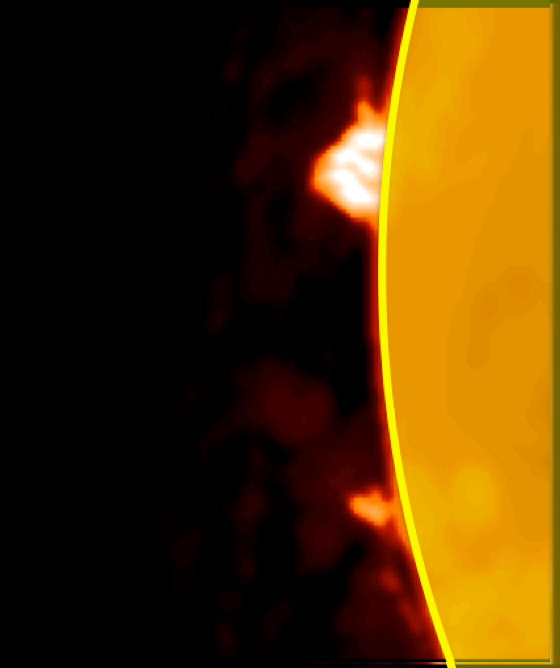


In contrast, Jupiter's closed magnetic field is ~20x size of planet, pulled open by plasma belt and solar wind



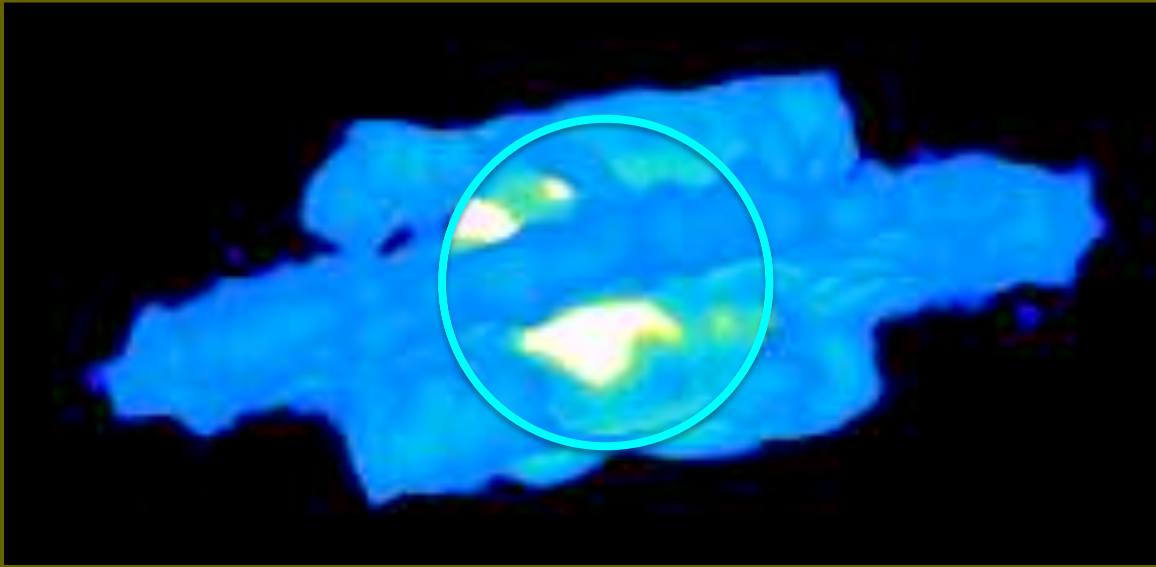
A large-scale closed magnetic field enables much larger radio structures (compared to size of star/planet)

Solar flare, 17 GHz



Stephen White/
Nobeyama Radioheliograph

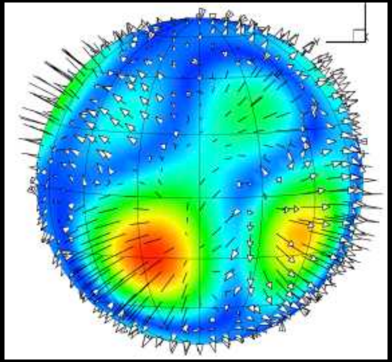
Jupiter's synchrotron belts, 1.4 GHz



de Pater & Sault 1998 / ATNF

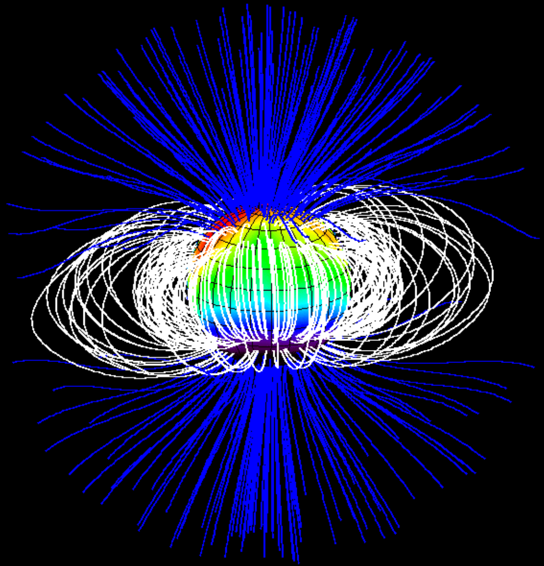
Stars' magnetic fields are mapped using polarized Zeeman splitting in optical absorption lines

Sun



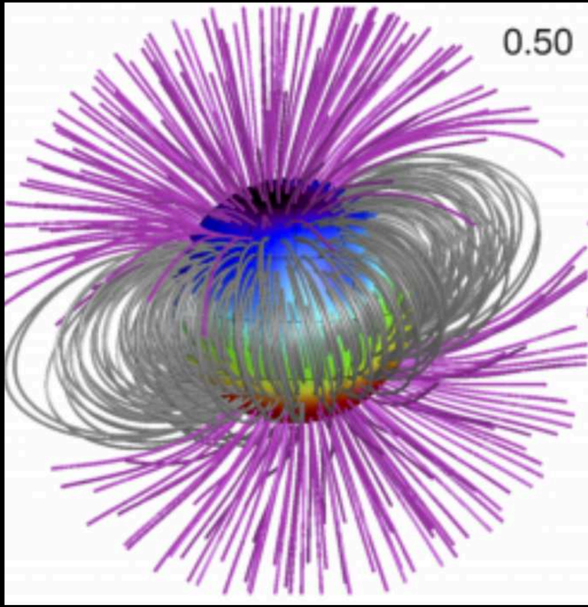
Vidotto 2016

Young M dwarf



Jardine & Donati

Magnetic Ap star

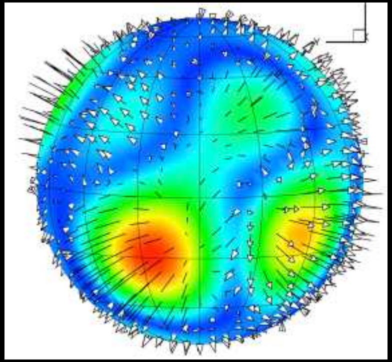


James Silvester

Magnetically active stars have much stronger global magnetic field than Sun → big closed field and big radio structures?

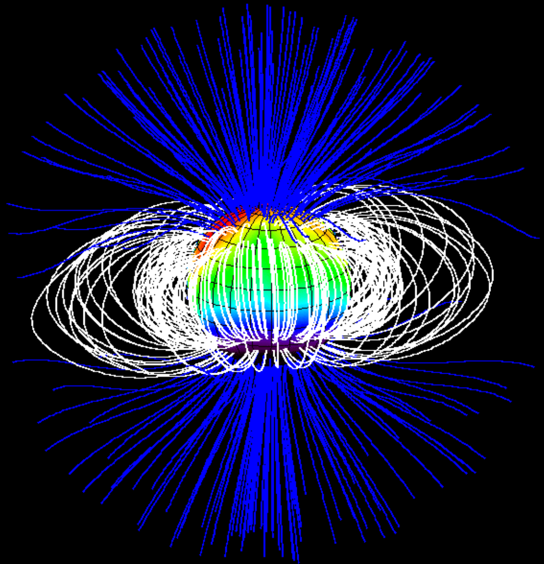
The magnetic dipole field of a young M dwarf is 500x stronger than the Sun's!

Sun



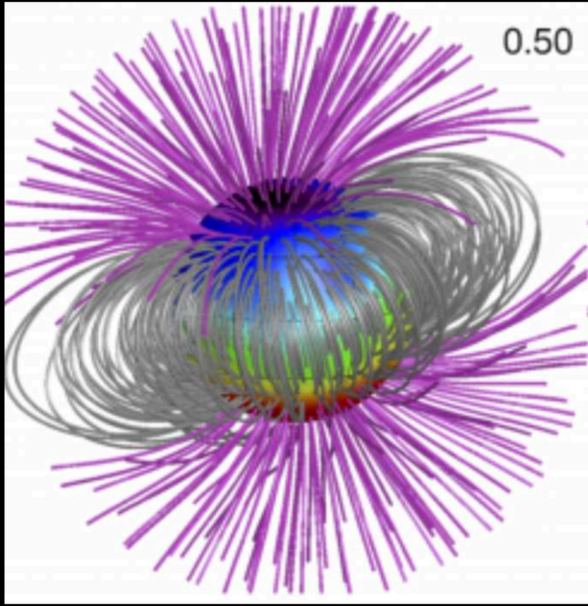
Vidotto 2016

Young M dwarf



Jardine & Donati

Magnetic Ap star



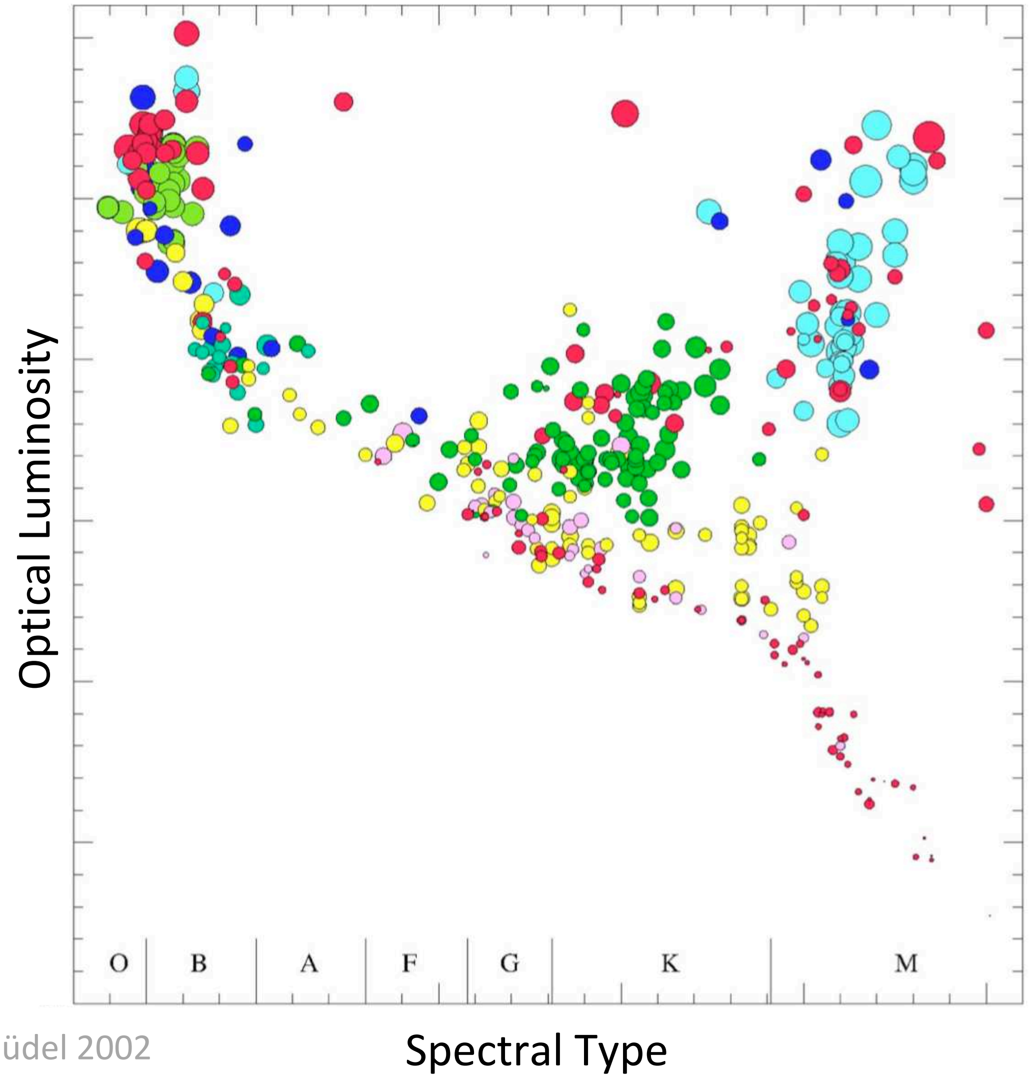
James Silvester

What type of (sub)stellar objects have magnetic activity observed in radio?

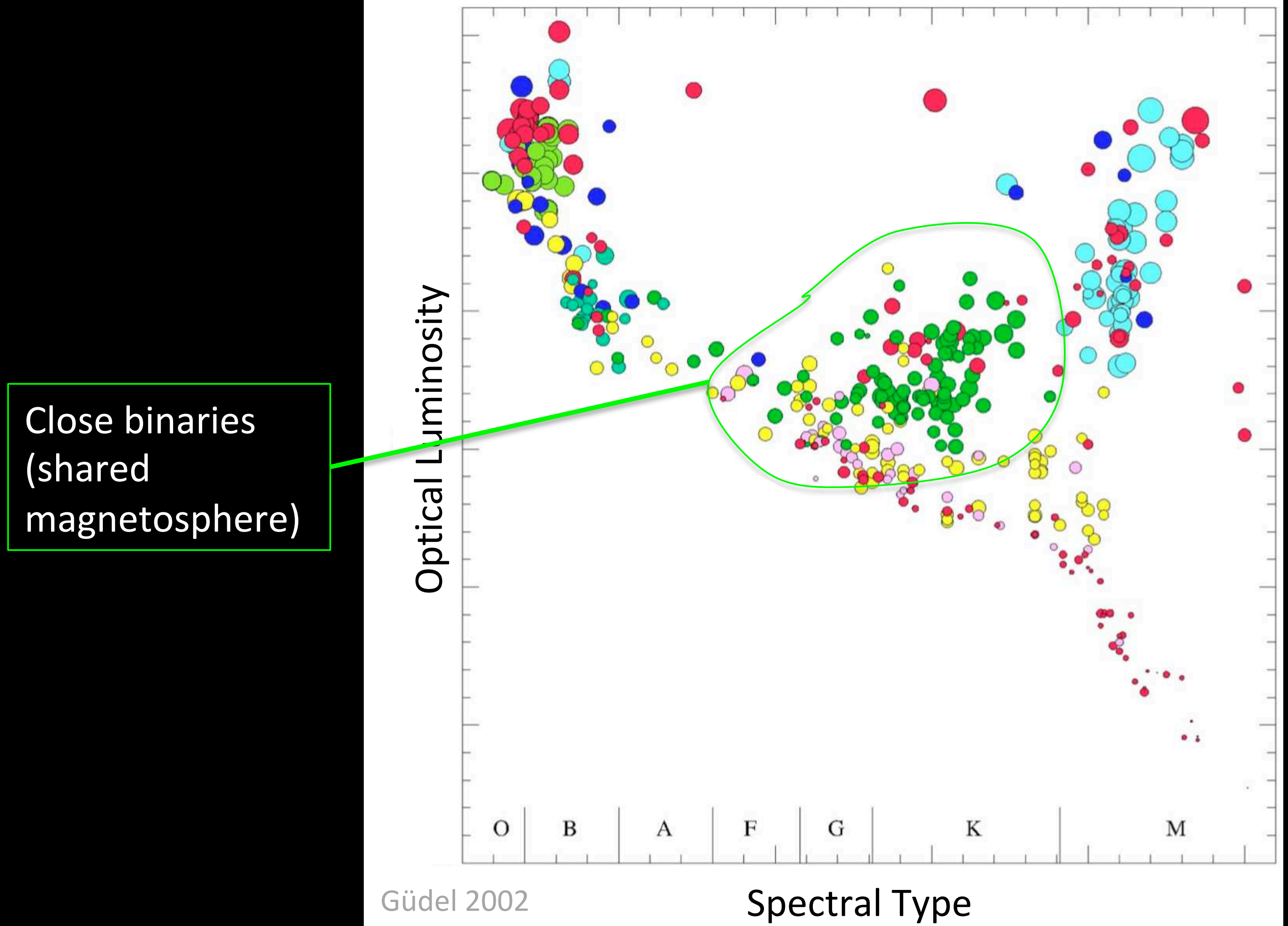
All radio-detected stars in 2002

(Güdel 2002)

- **Magnetic activity**
- Radiative winds
- Thermal photosphere (giant stars)



Güdel 2002

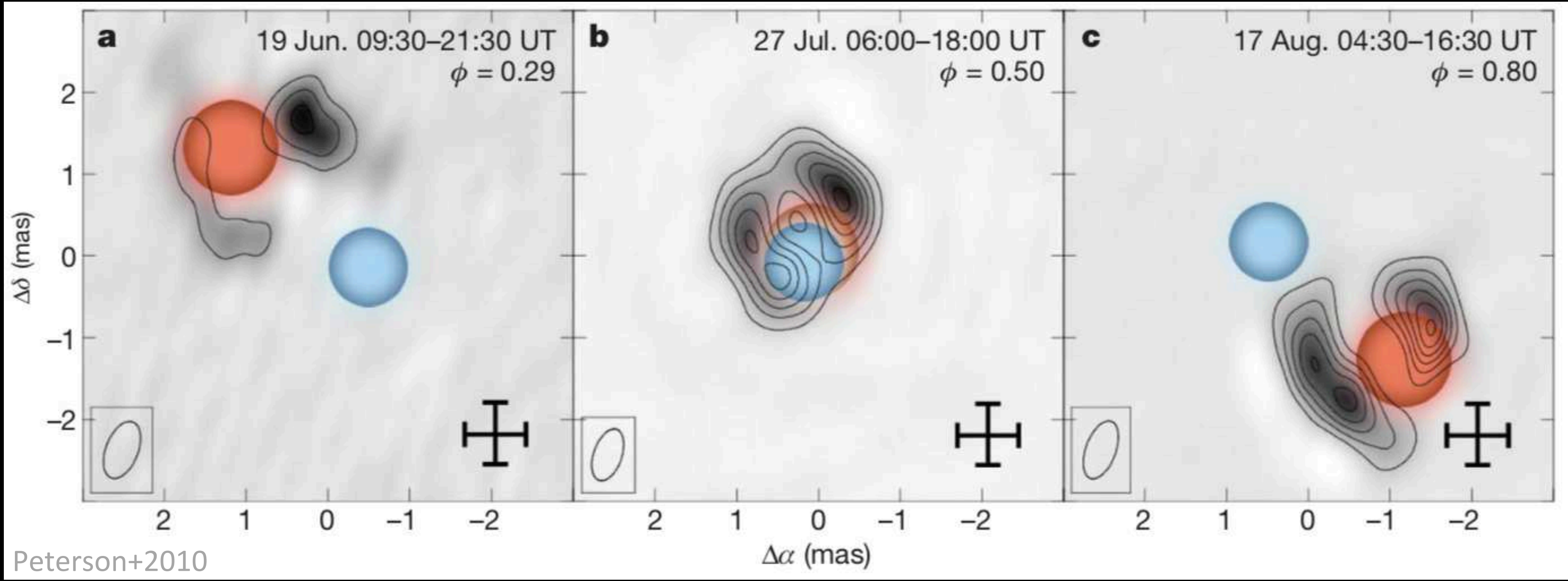


Close binaries (shared magnetosphere)
Optical Luminosity
O
B
A
F
G
K
M
Spectral Type
Güdel 2002

In a close binary, magnetic interaction causes large magnetic loop on secondary star

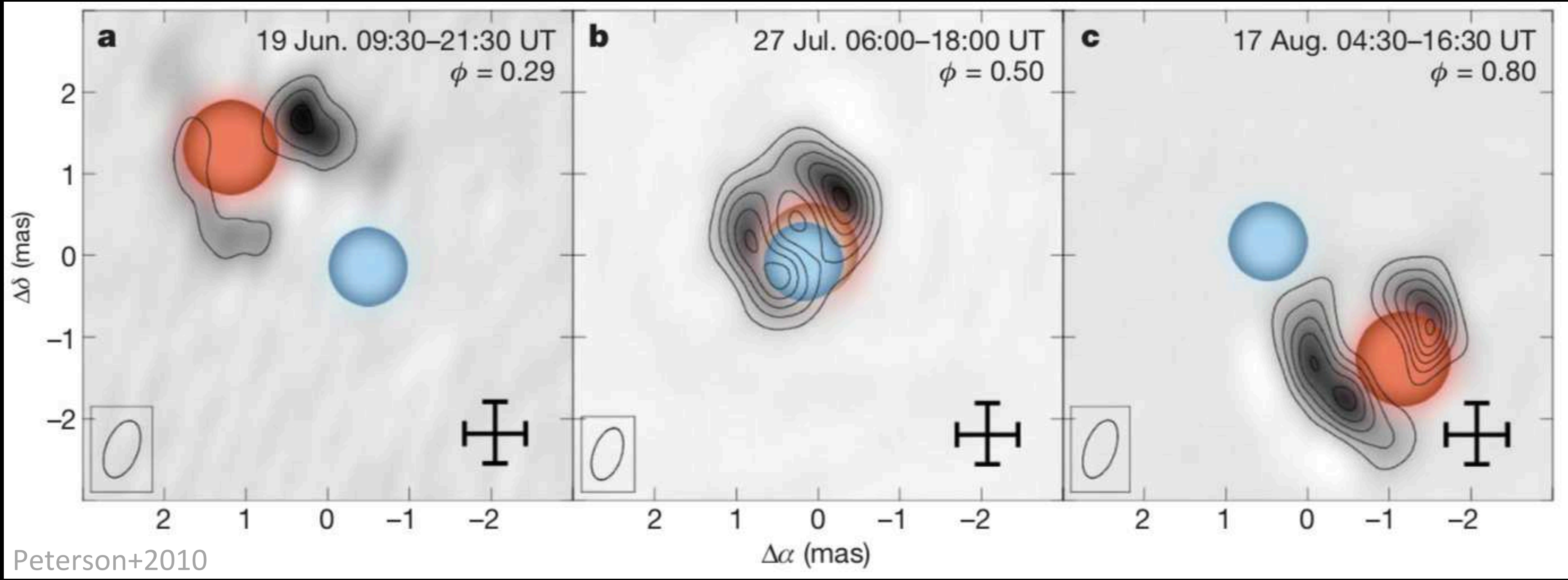
Algol: B8 + KIV Rapid (2.9 day) orbit causes stars to rotate fast, driving strong B field

15 GHz In close binaries, radio emission tends to be associated with secondary

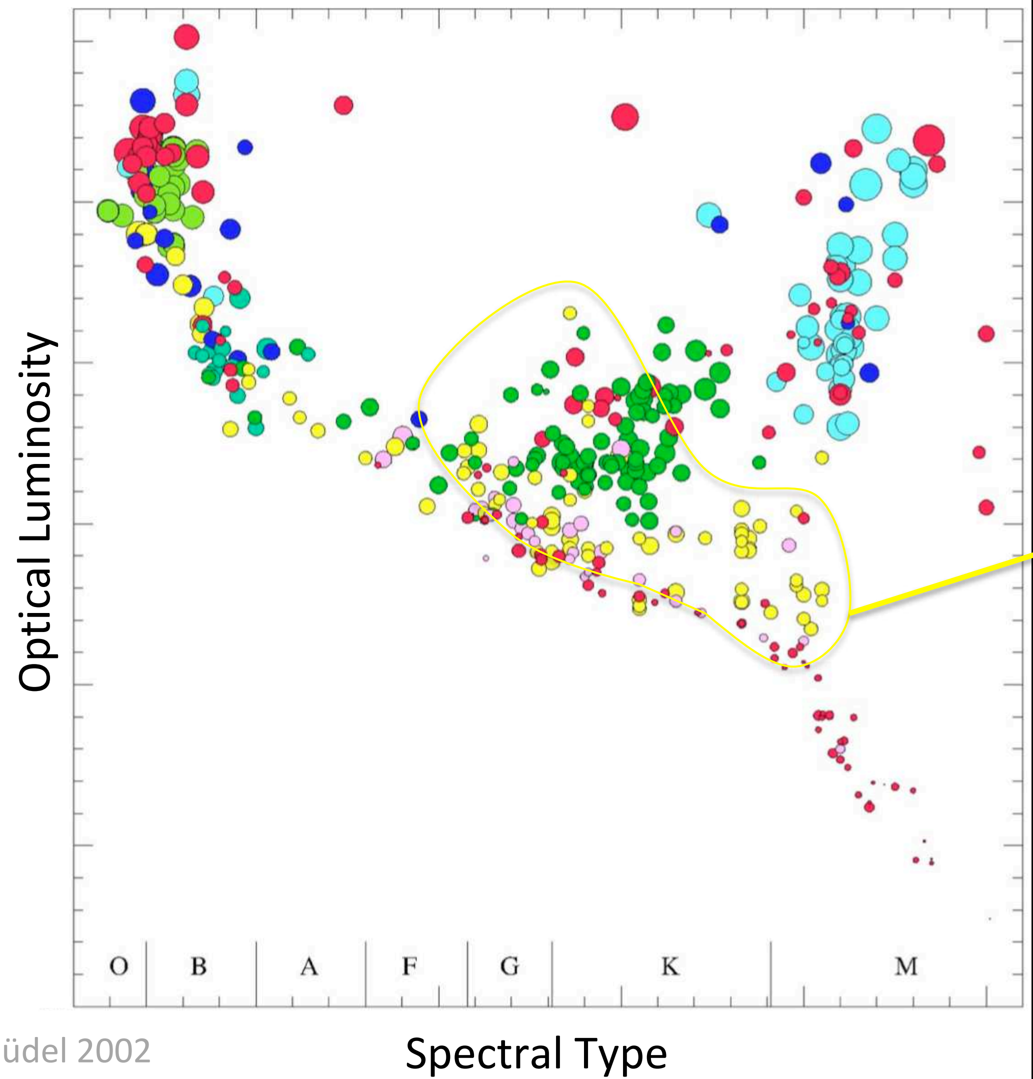


Peterson+2010

Large magnetic loop attached to magnetic poles is more like Jupiter than the Sun



Close binaries (shared magnetosphere)

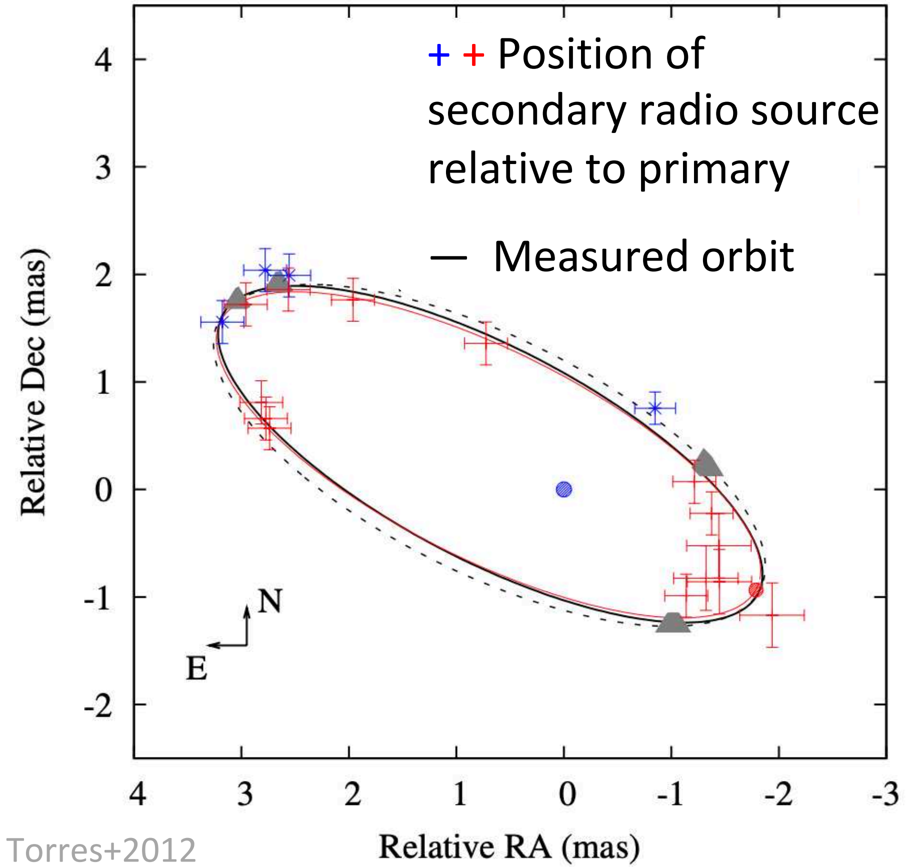


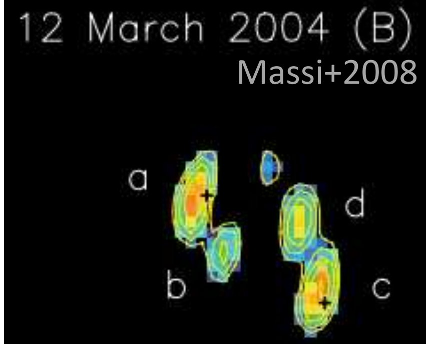
Güdel 2002

Young stellar objects

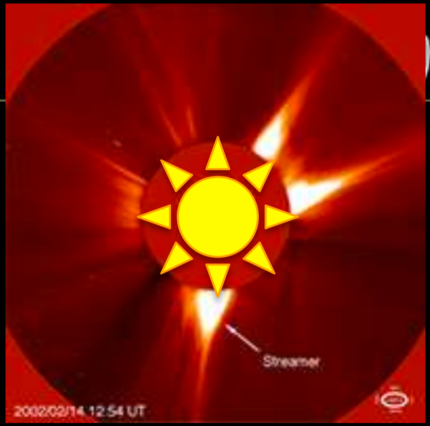
(astrometry talk by Gisela Ortiz-Léon)

Young stars in an elliptical binary show evidence of magnetic interaction at periastron





Helmet streamers?



V773 Tau A — 8.3 GHz

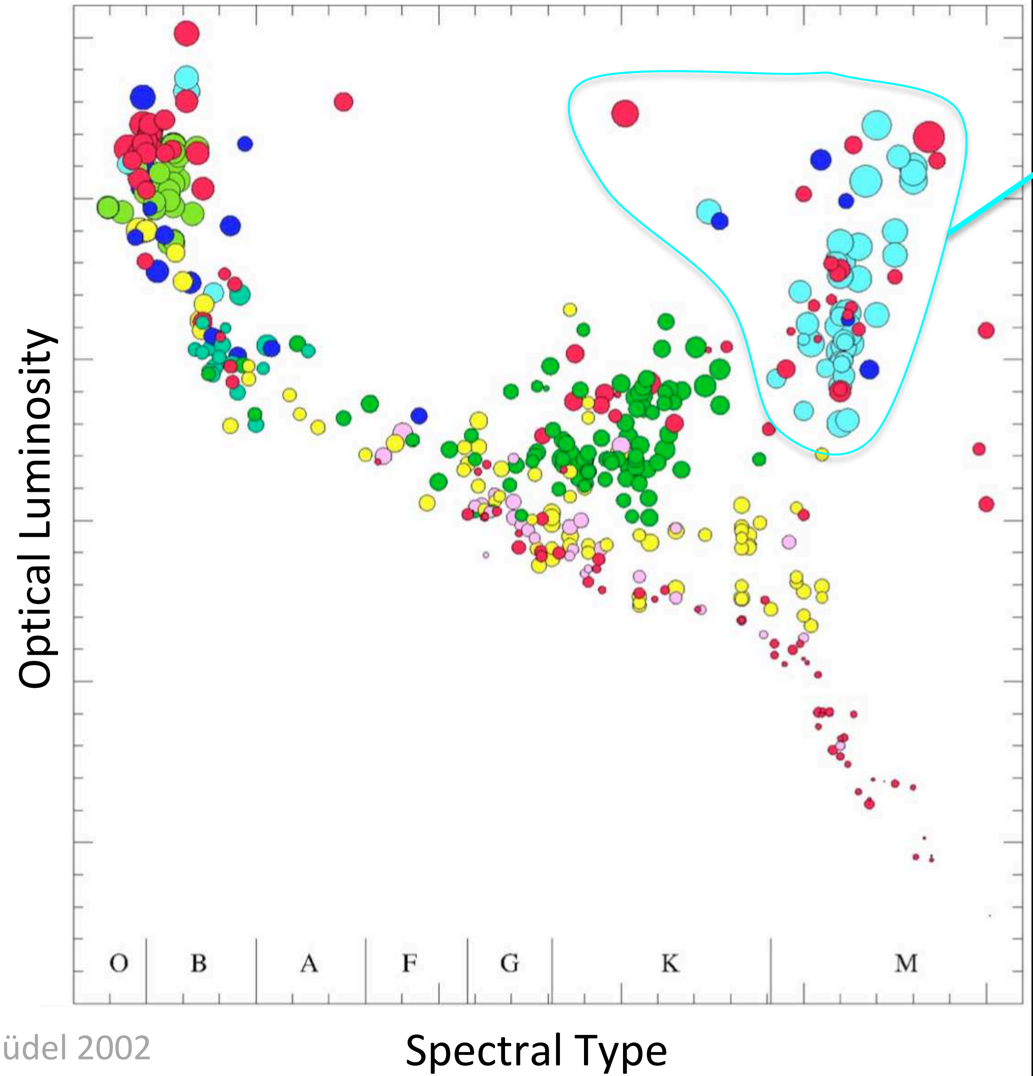
Torres+2012: 27 epochs VLBA

Sources resolved ~50% of epochs, 2.5-3.5 D_*

Massi+2008: Effelsberg + VLBA, 1 of 7 epochs

Double sources not seen in 27 epochs of VLBA-only by Torres+12

Close binaries (shared magnetosphere)

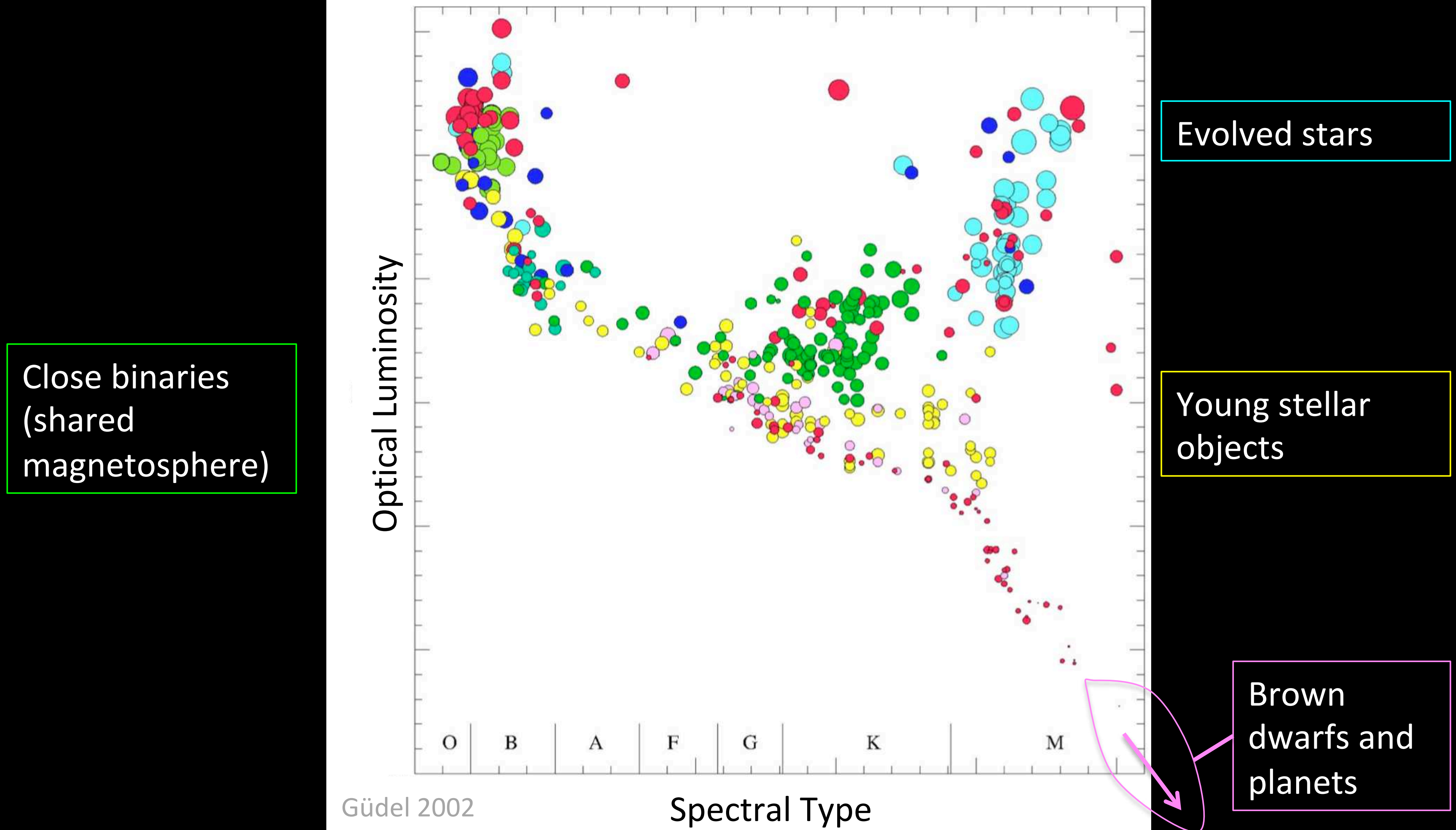


Güdel 2002

Evolved stars

(chromospheres and binaries? - talk by Elizabeth Humphreys)

Young stellar objects


Close binaries (shared magnetosphere)
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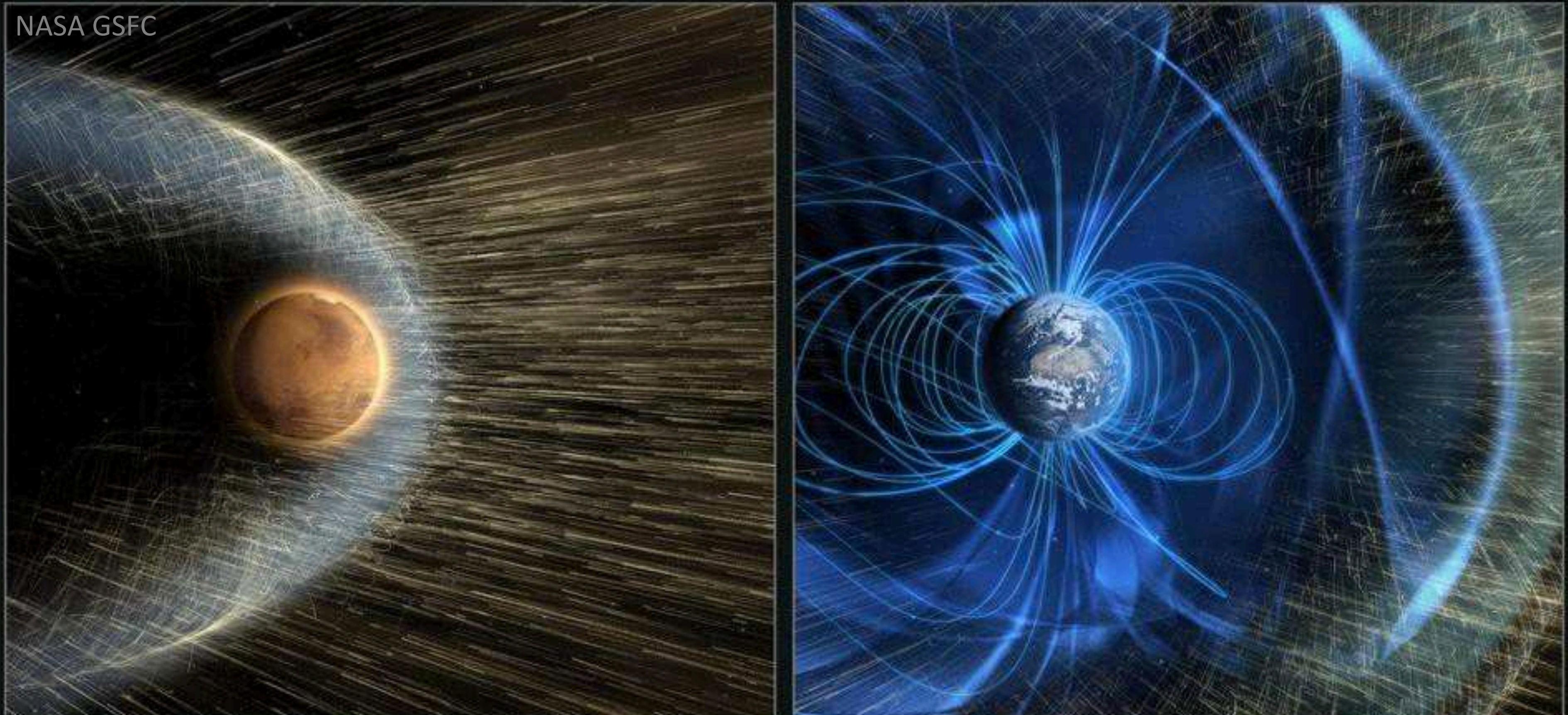
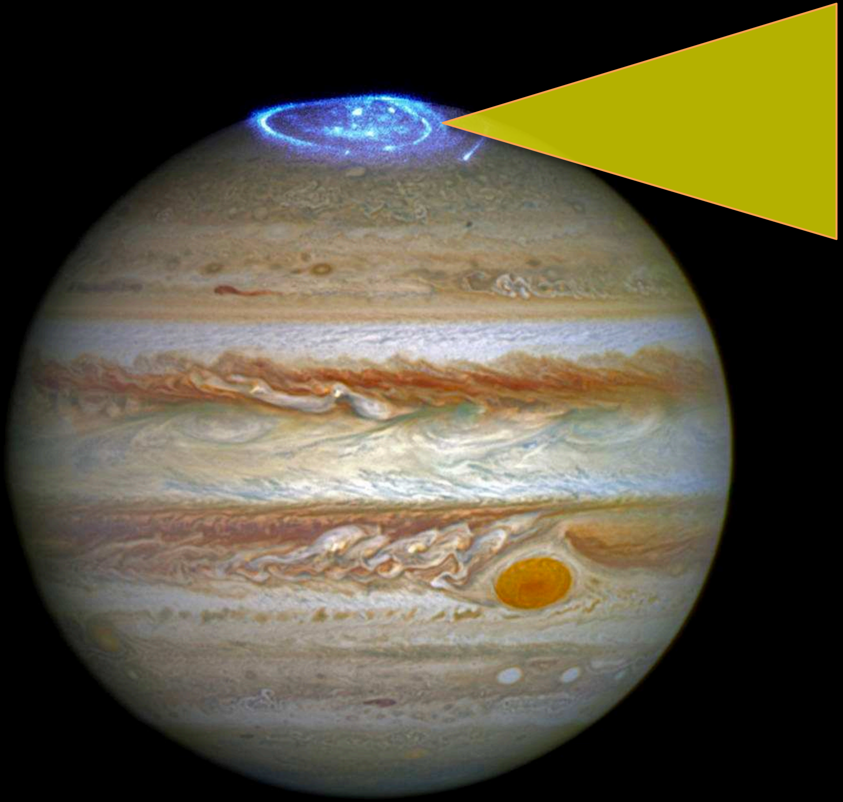
Young stellar objects
Brown dwarfs and planets

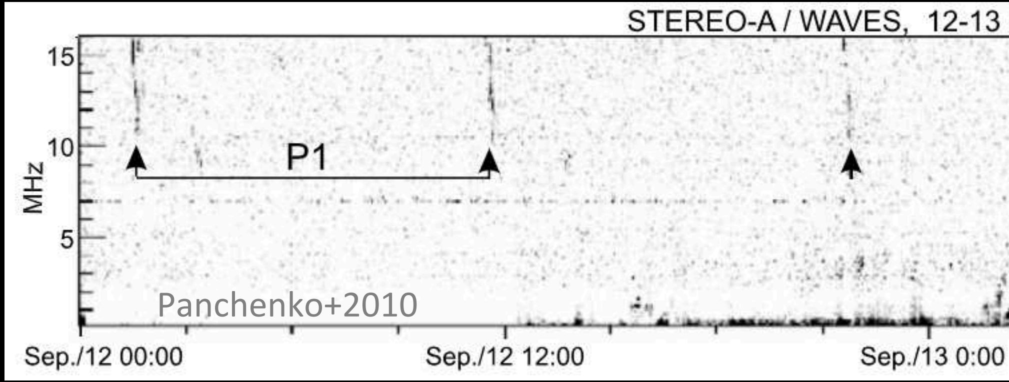
Güdel 2002

Planetary magnetic fields are important for habitability



Planetary magnetic field strength can be measured from a radio aurora – a “slow pulsar”





A radio aurora is periodic coherent radio bursts, produced at the cyclotron frequency by an electron cyclotron maser (ECM)

Image credit: NASA/ESA/J. Nichols

Planetary magnetic field strength can be measured from a radio aurora – a “slow pulsar”

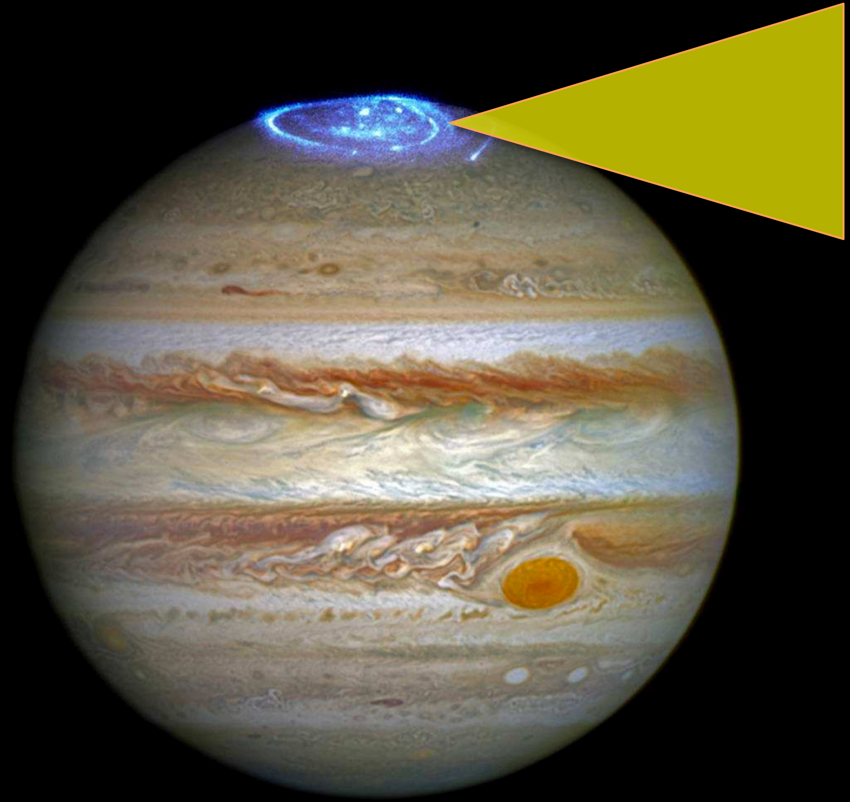
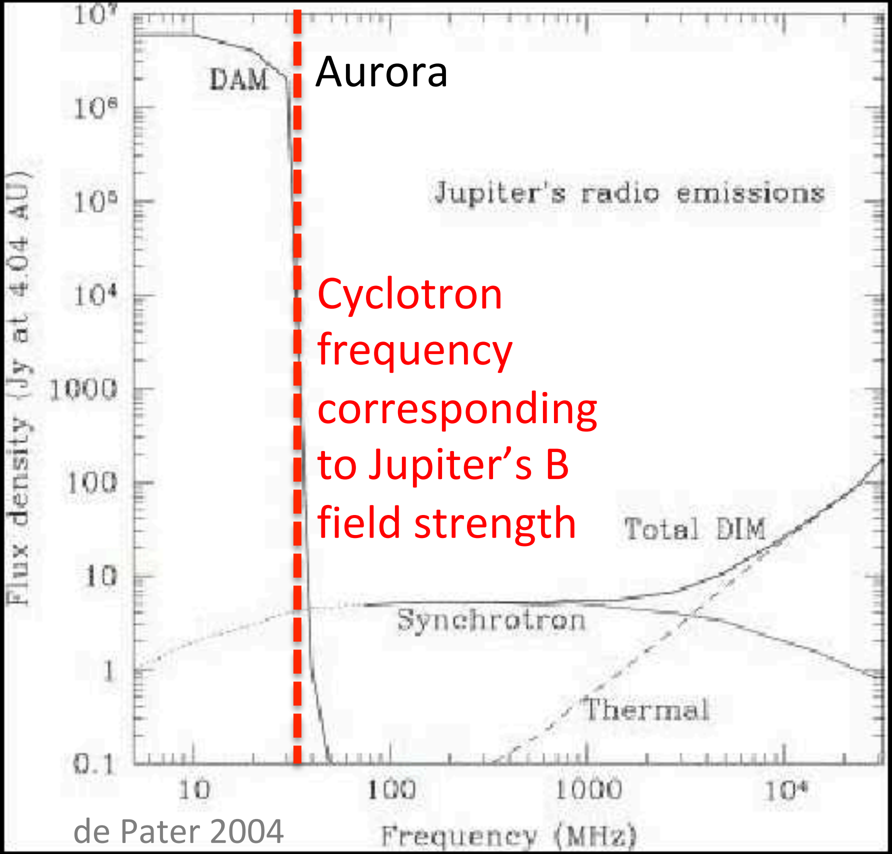
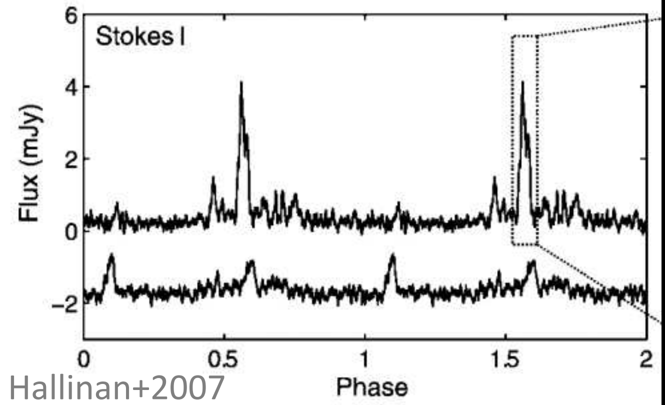


Image credit: NASA/ESA/J. Nichols

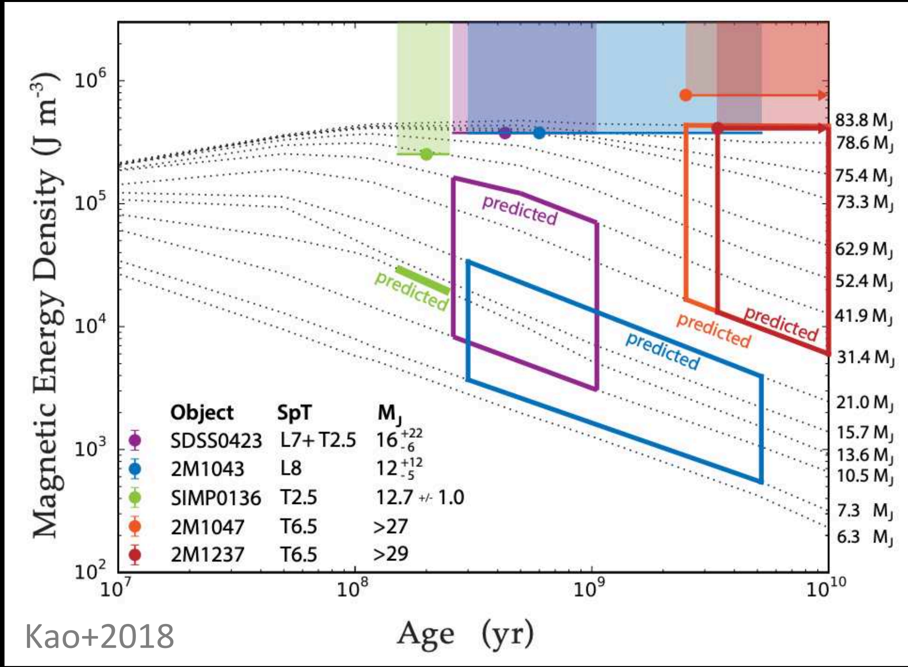


de Pater 2004

We have not yet detected radio aurorae on exoplanets, but brown dwarfs can serve as "radio exoplanet analogs"



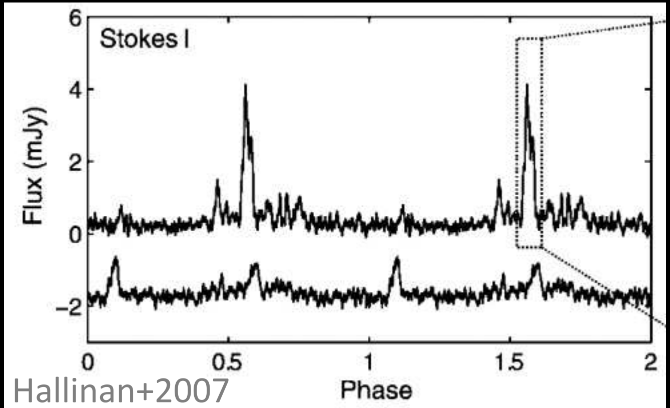
Hallinan+2007

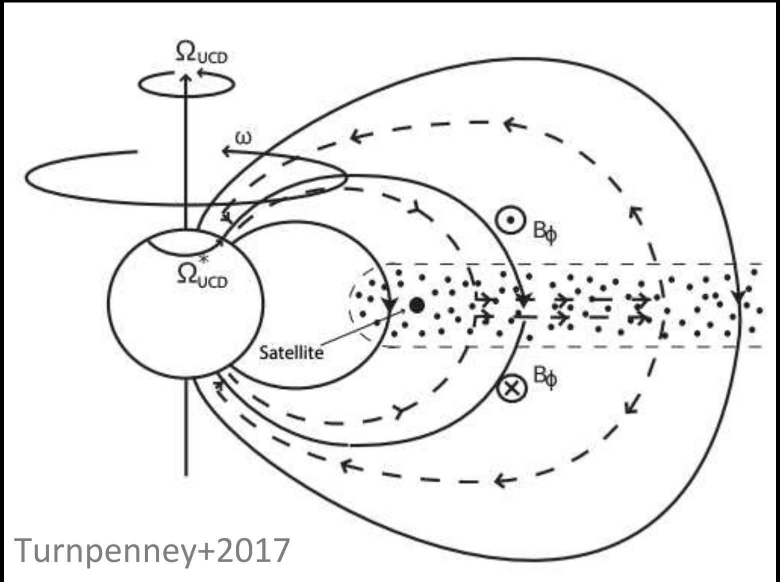


Kao+2018

Kao+2018: First radio aurora on free-floating planetary-mass object – implies young Jupiters may have much stronger B fields than predicted

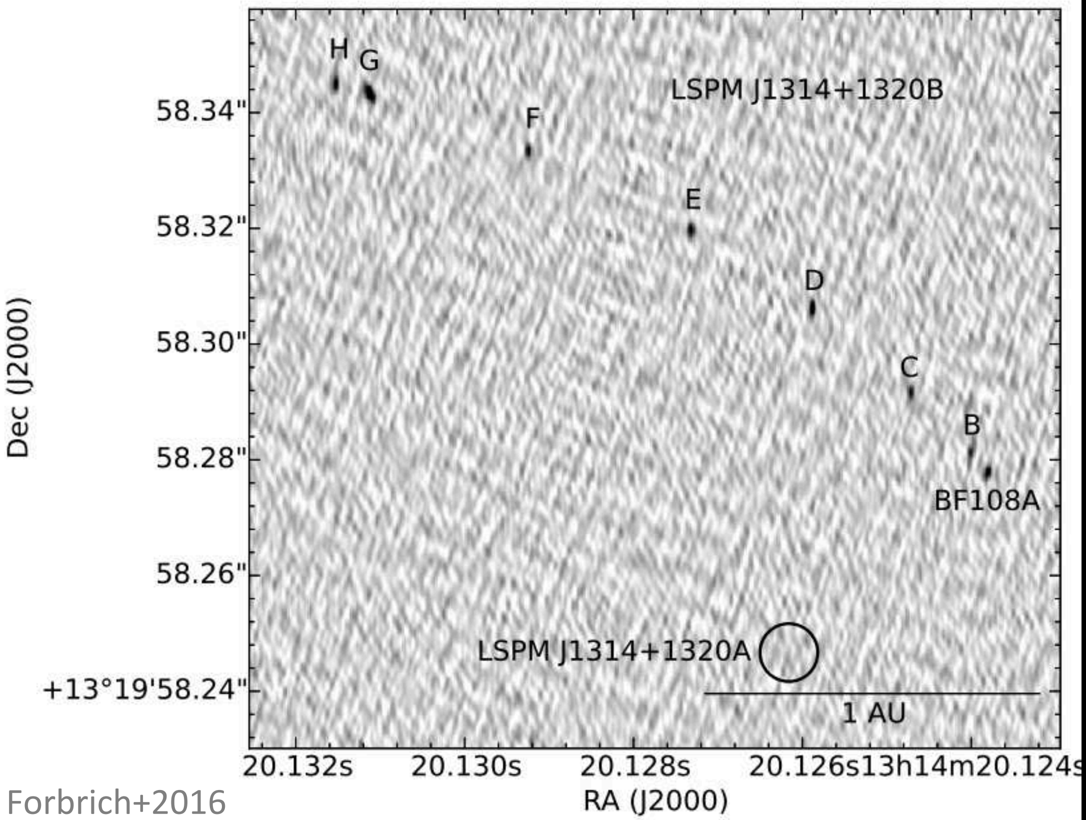
Without a hot corona causing a wind, brown dwarfs may have very large closed magnetic fields





Turnpenney+2017 (theory): Brown dwarfs may have closed magnetospheres 500x larger than photosphere!

Brown dwarf VLBI observations indicate compact emission, enabling radio source identification in binary



Forbrich+2016

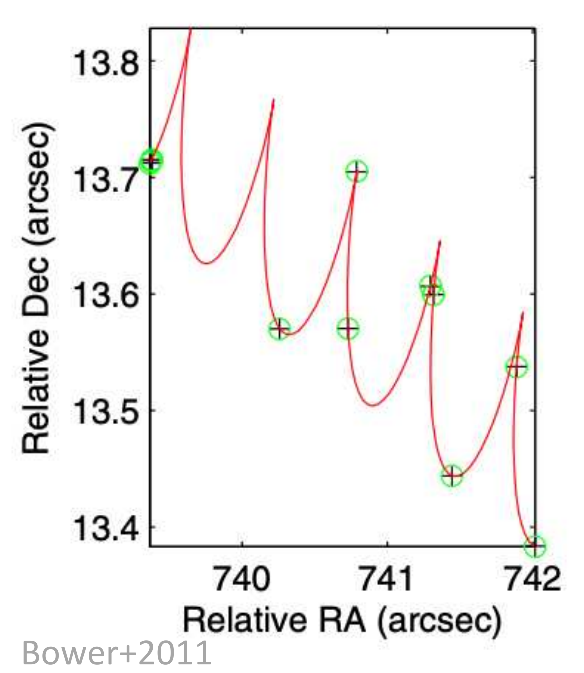
Forbrich+2016: Used VLBI to identify quiescent radio source in brown dwarf binary

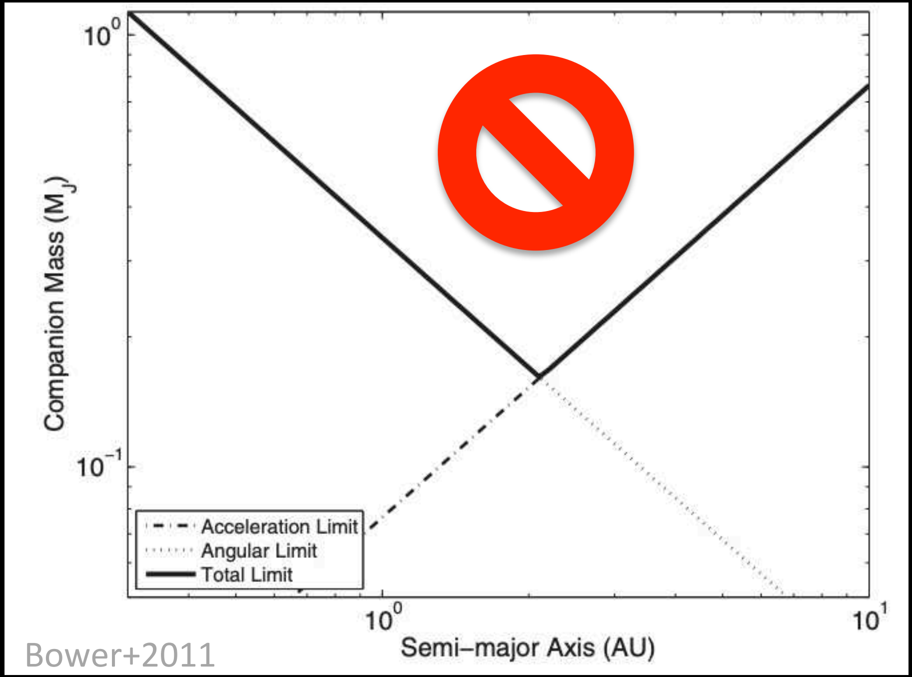
(unresolved in all epochs)

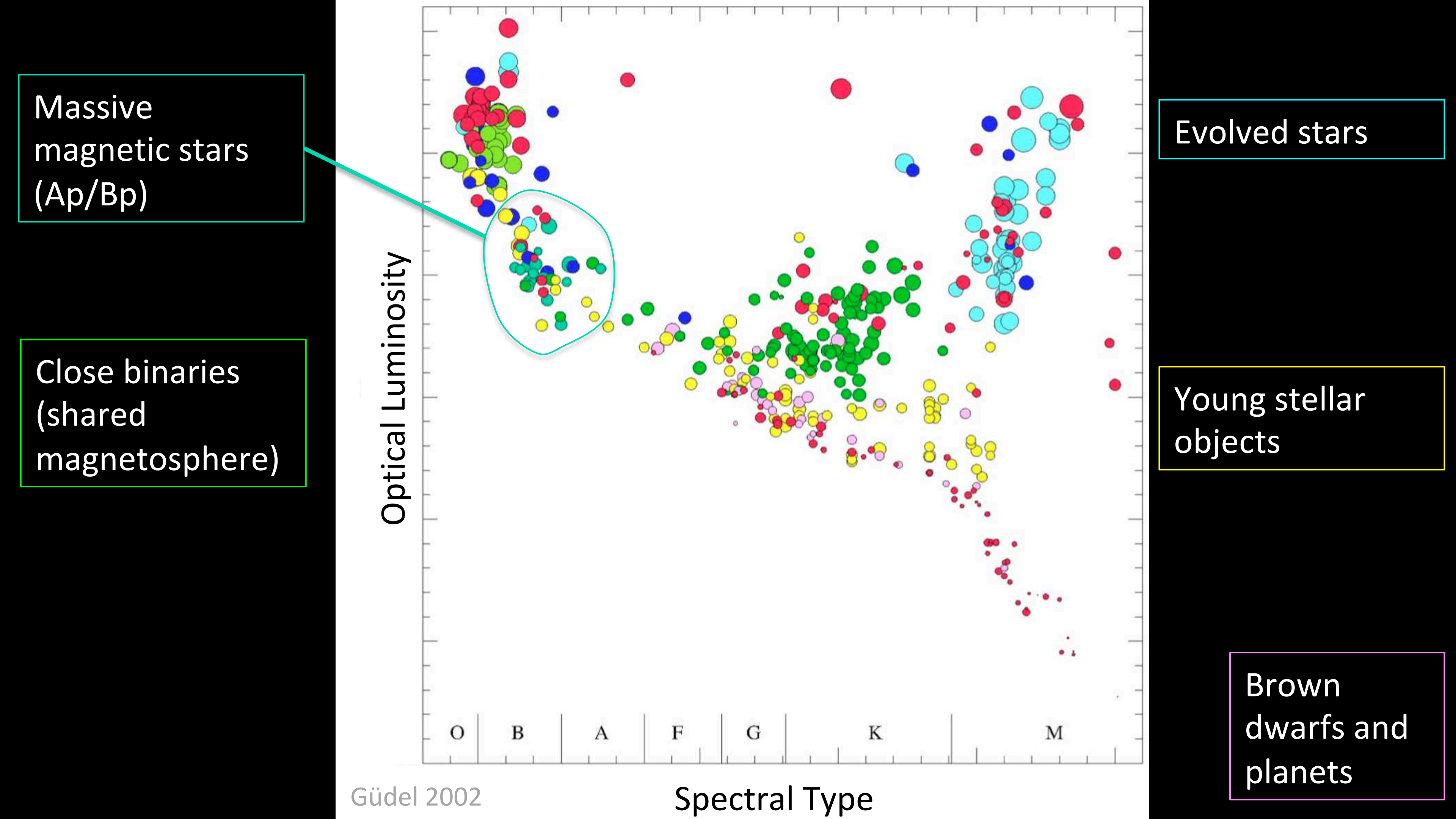
Potential future role of VLBI: test planetary origin of radio signals

VLBI stellar astrometry – an exoplanet search tool

RIPL – Astrometric planet search around active M dwarfs – ruled out companions > 0.15M_J at 2 AU for EQ Peg A (Bower+09,11)






Massive magnetic stars (Ap/Bp)
Close binaries (shared magnetosphere)
Evolved stars
Young stellar objects
Brown dwarfs and planets
Optical Luminosity
Spectral Type
O
B
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F
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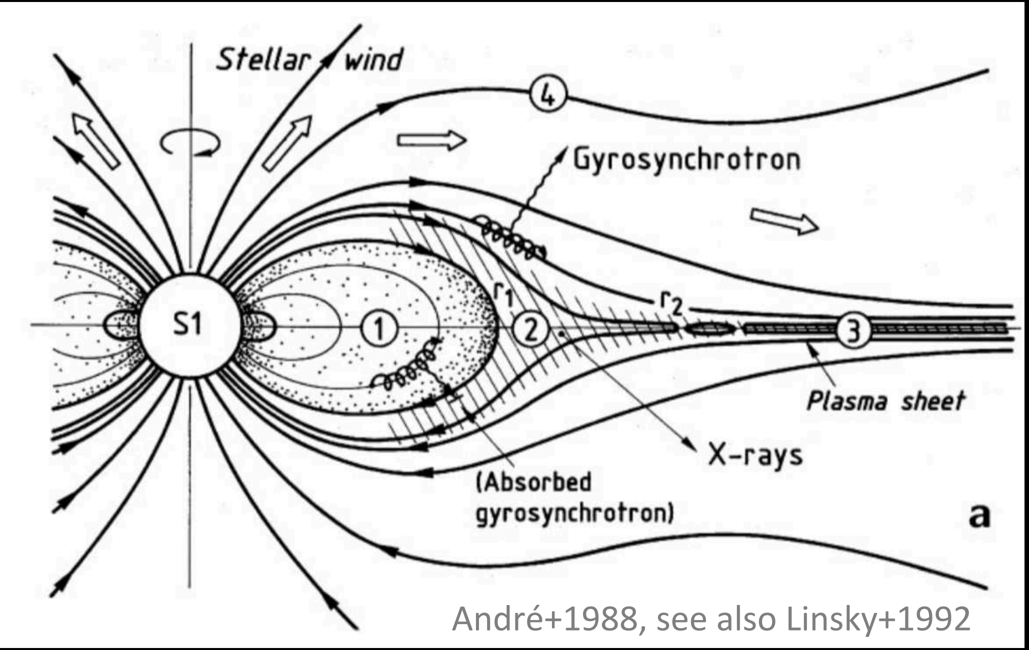
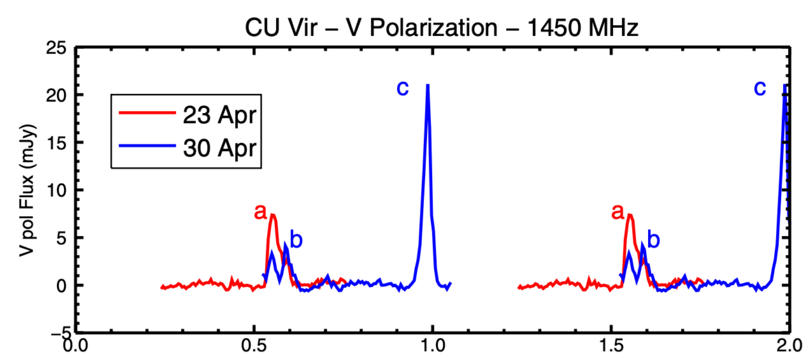
K
M

Güdel 2002

The radio emission from magnetic massive stars (Ap/Bp) is modeled as a large-scale process; some have radio aurora like Jupiter



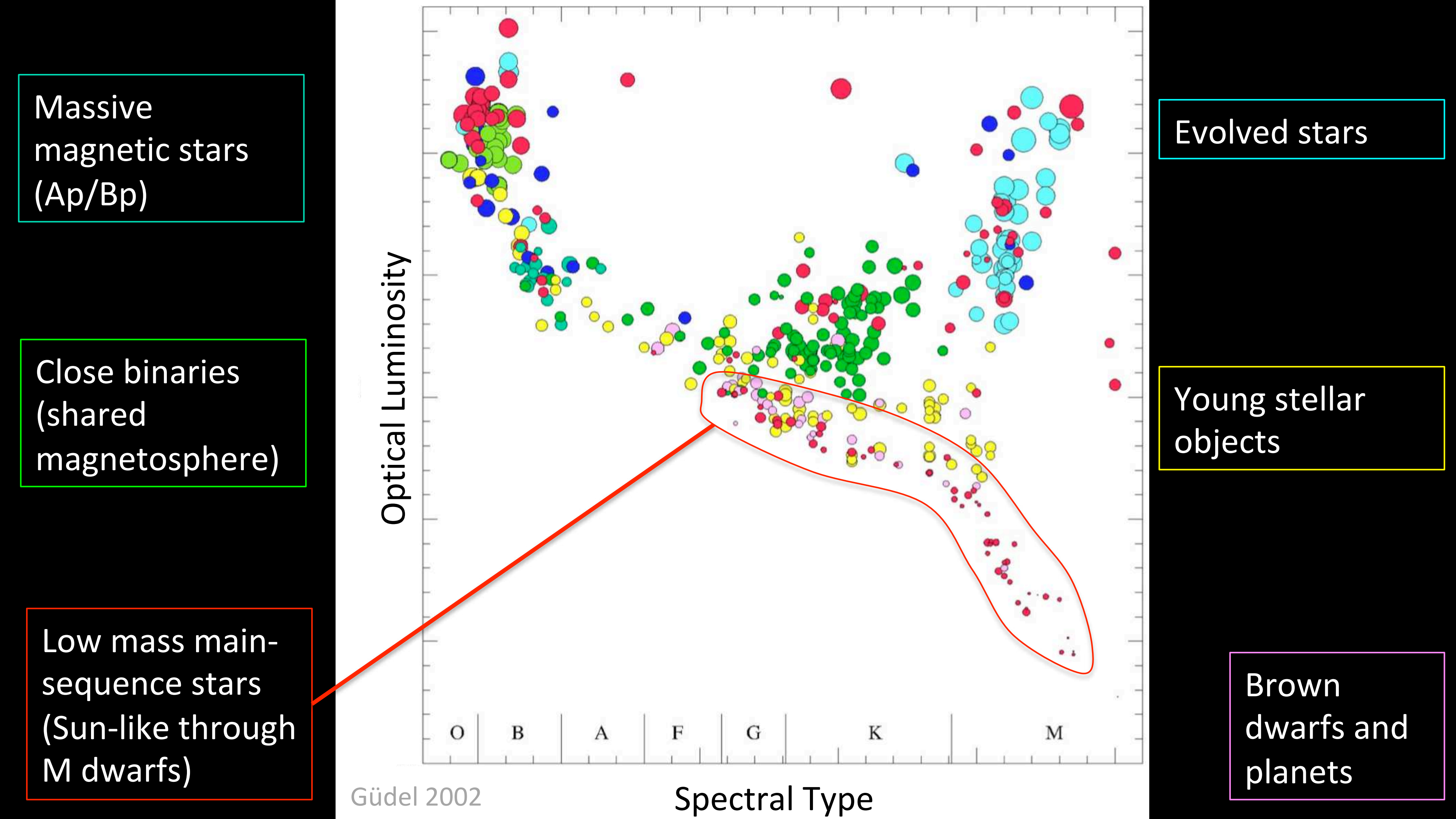
André+1988, see also Linsky+1992



Trigilio+2011

Phillips & Lestrade 1988: radio size <= 6 stellar diameters

Significant potential for testing model through further VLBI studies!

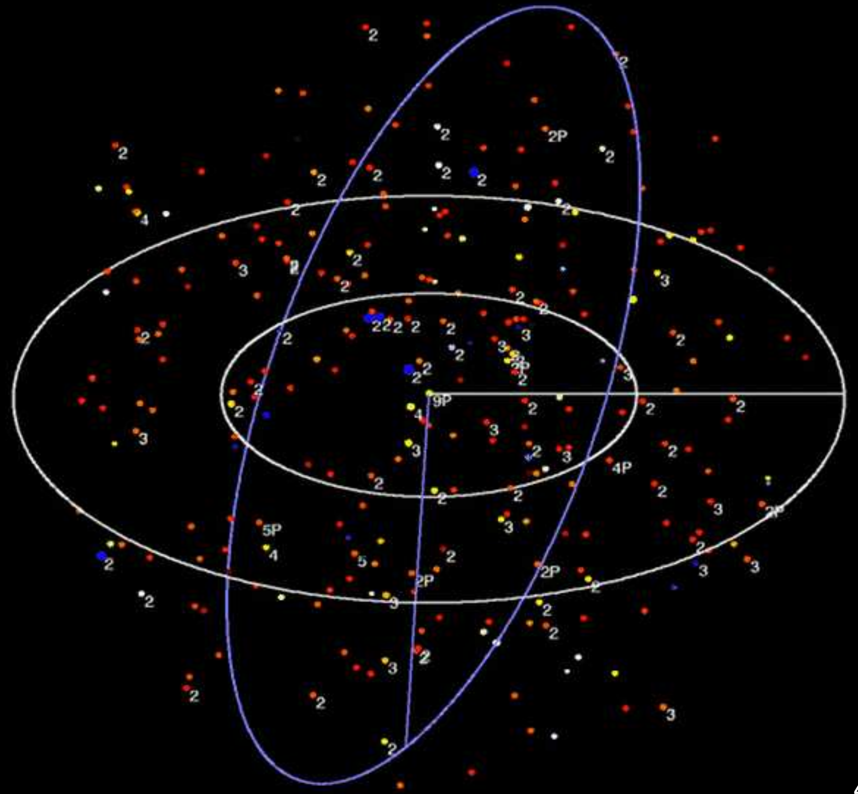


Massive magnetic stars (Ap/Bp)
Close binaries (shared magnetosphere)
Low mass main-sequence stars (Sun-like through M dwarfs)
Evolved stars
Young stellar objects
Brown dwarfs and planets
Optical Luminosity
O
B
A
F
G
K
M
Spectral Type
Güdel 2002

The nearest Earth outside our solar system is probably around a red dwarf

75% of stars are red dwarfs
(Henry et al. 2018)

Most red dwarfs have planets
(Dressing & Charbonneau 2015)



Stars within 30 light years.
Image credit: A. Riedel, T. Henry, and RECONS.

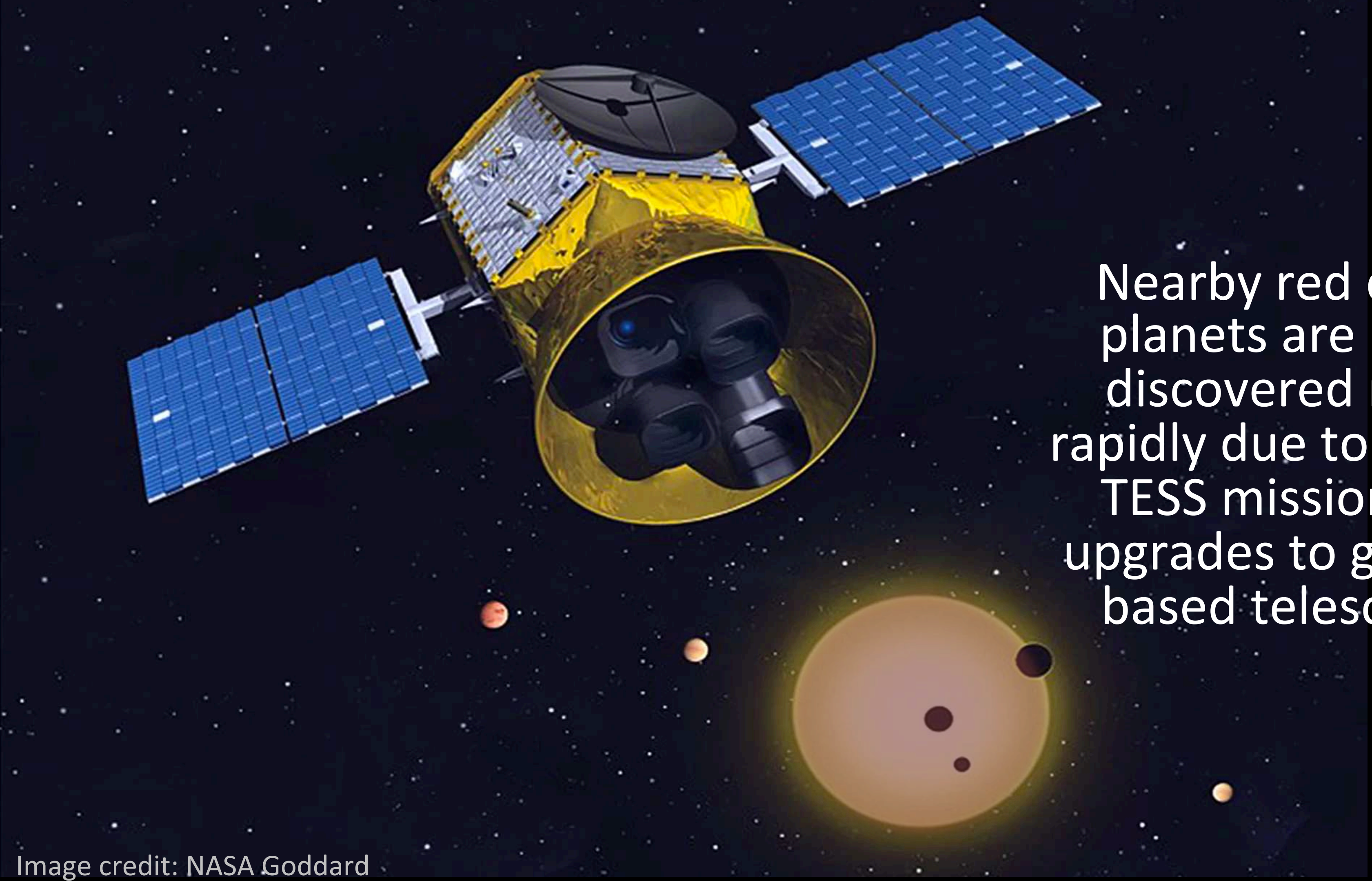
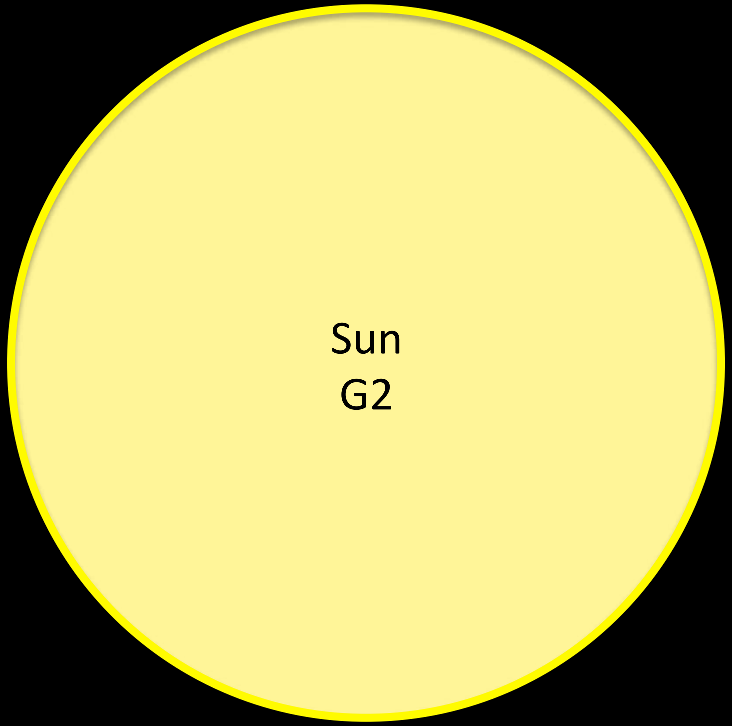


Image credit: NASA Goddard

Nearby red dwarf planets are being discovered more rapidly due to NASA’s TESS mission and upgrades to ground-based telescopes

The Sun’s quiet radio corona, and gyrosynchrotron flares, are close to the photosphere



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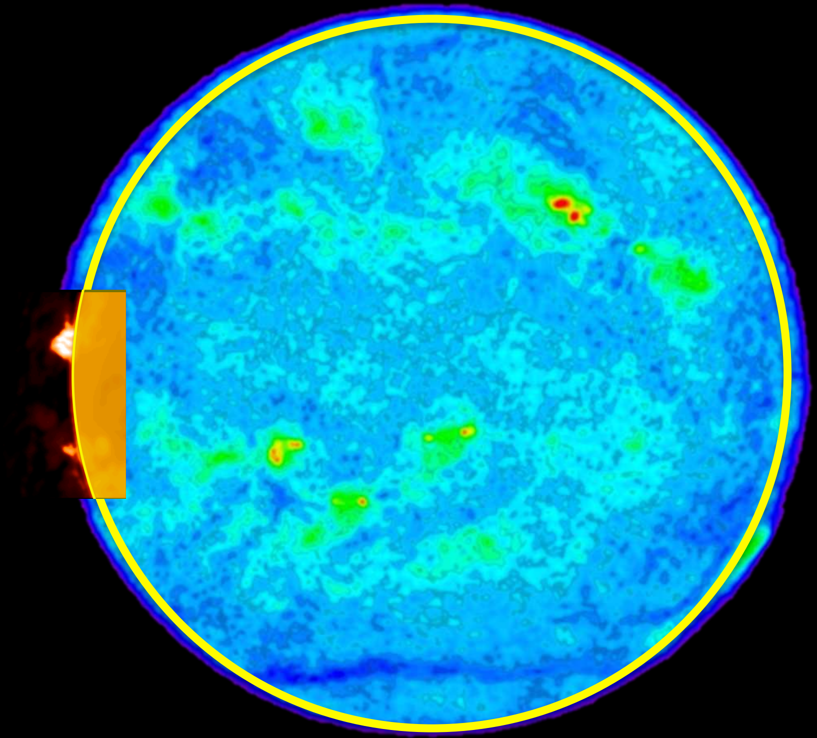
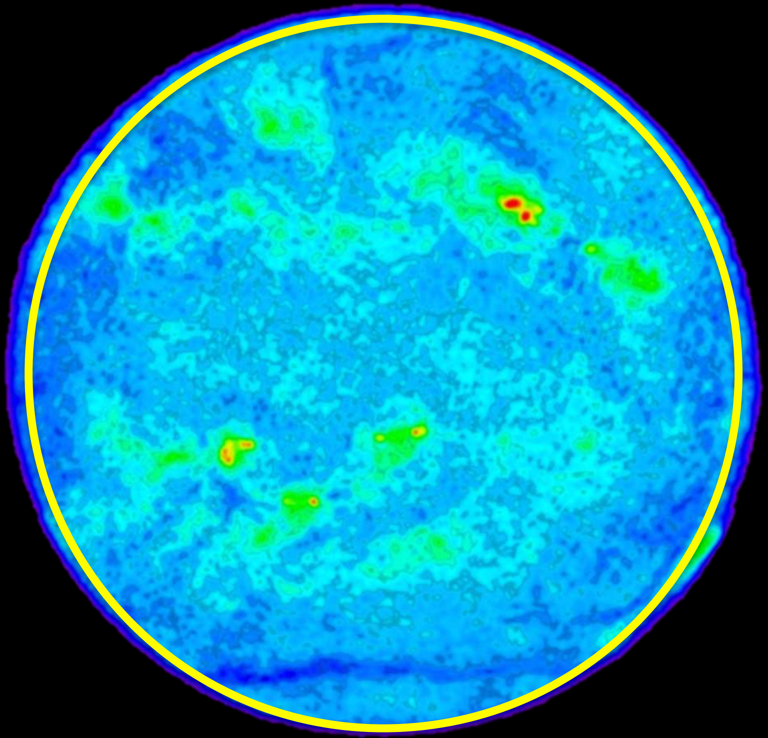


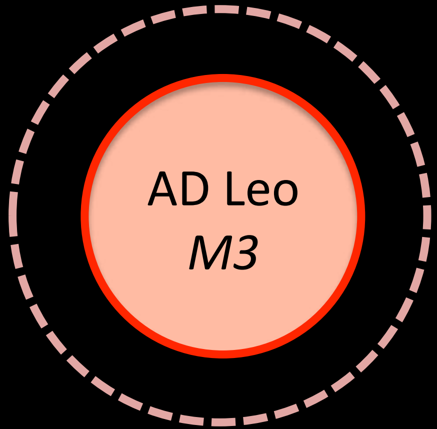
Quiet Sun at 5 GHz, 17 GHz flare. Stephen White.

First VLBI observations of active M dwarfs: astrometry at 1.4 GHz, unresolved



Quiet Sun at 5 GHz. Stephen White.

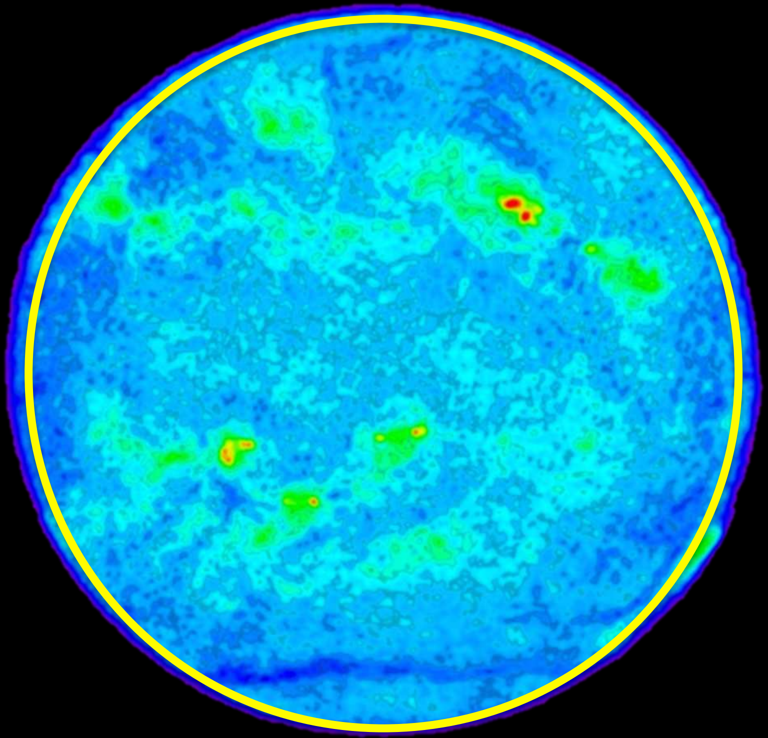
(photosphere physical size shown to scale)



Upper limit on quiescent radio source size (Benz+95)

Also: Benz & Alef 91

First resolved flare: 8.4 GHz, UV Cet



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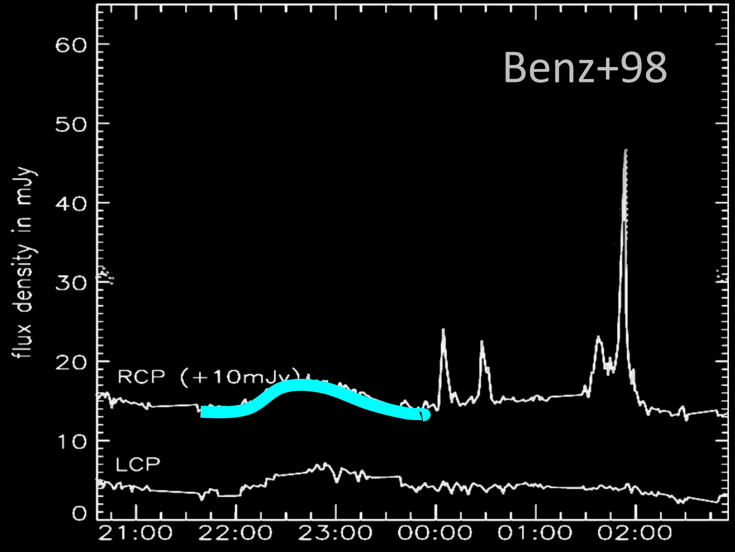
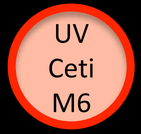
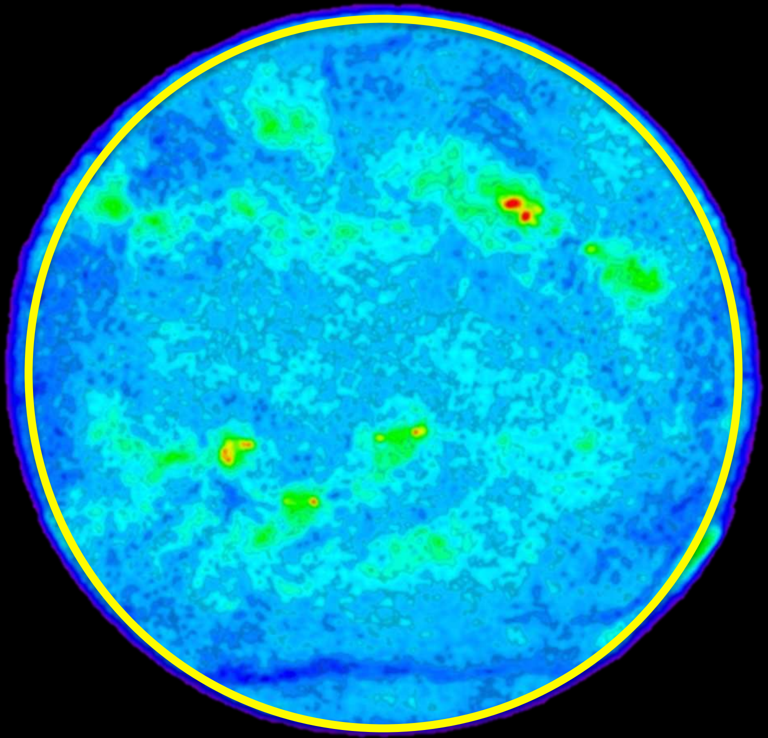


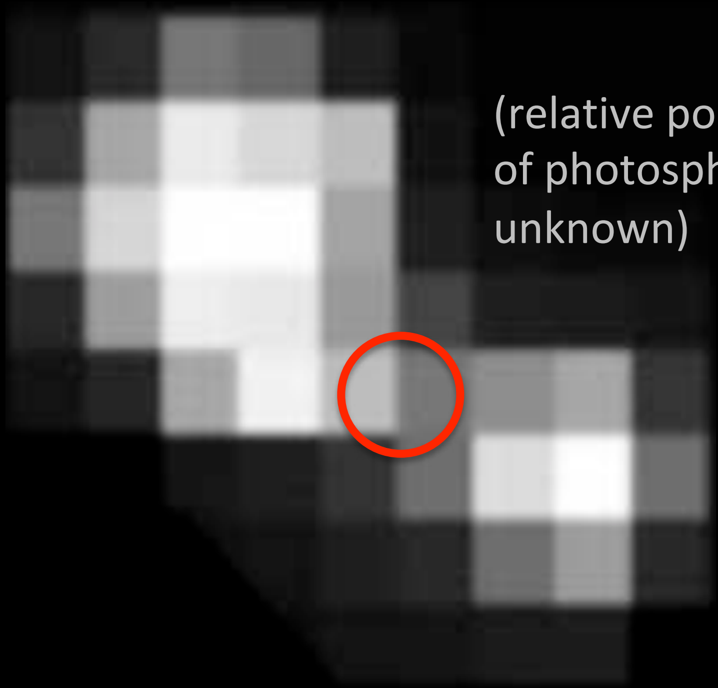


First resolved flare: 8.4 GHz, UV Cet

Benz+98



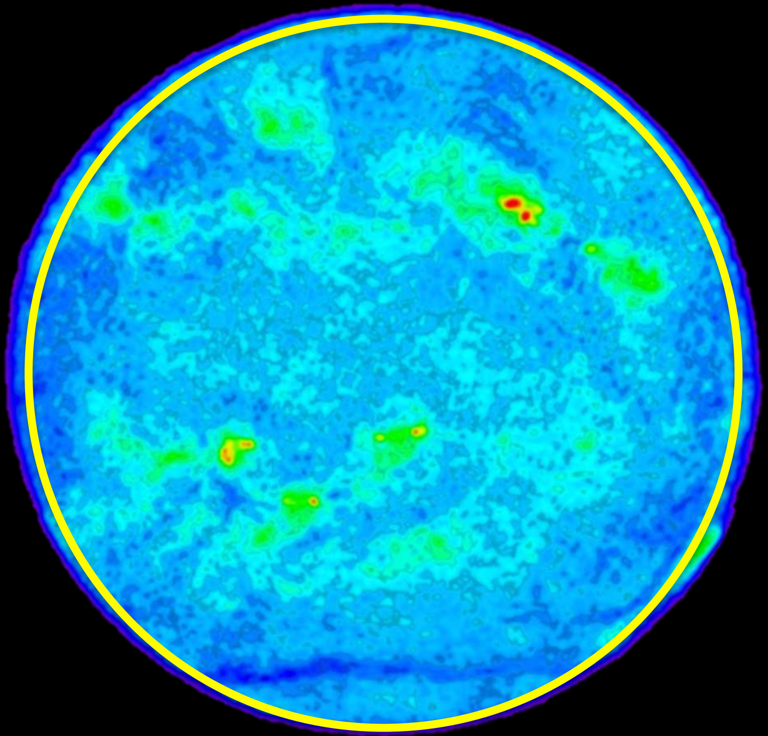
Quiet Sun at 5 GHz. Stephen White.



(relative position of photosphere unknown)

YZ CMi 8.4 GHz: quiescent + flares resolved

Pestalozzi+00



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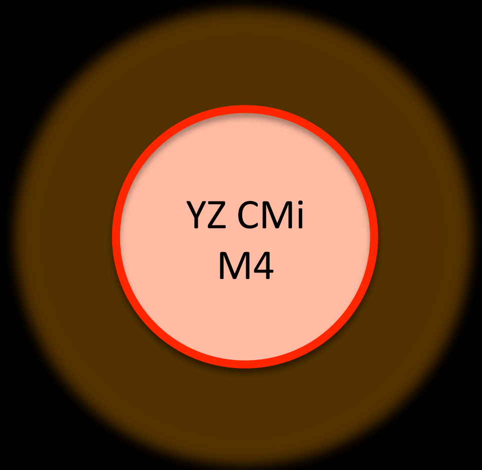
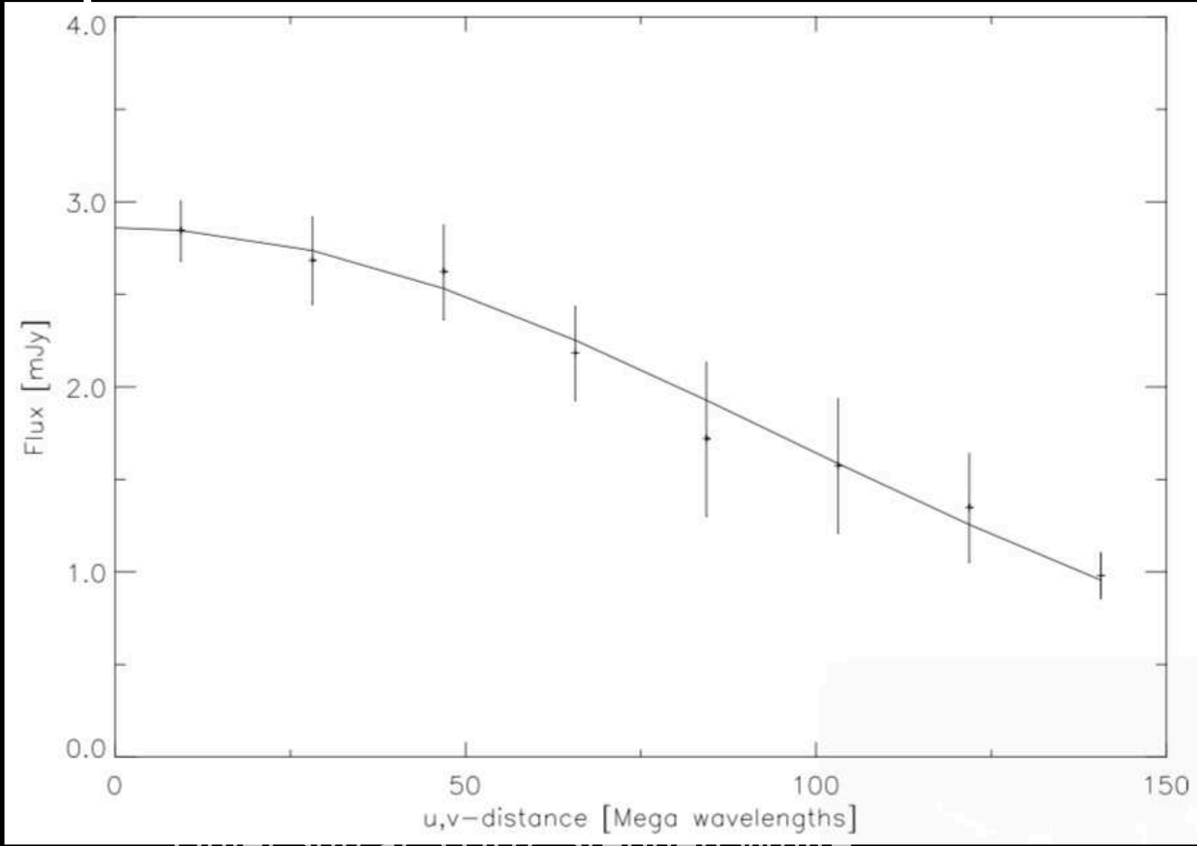
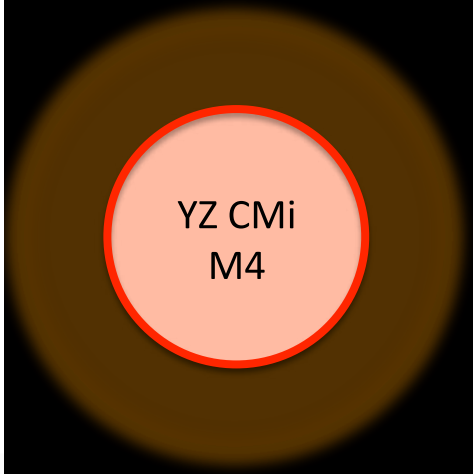


Radio source 1.7*photosphere
(Relative position not known)

YZ CMi 8.4 GHz: quiescent + flares resolved

Pestalozzi+00





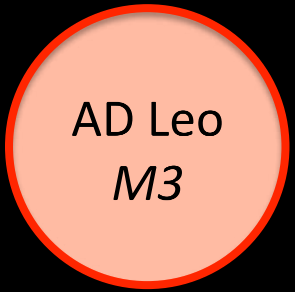
dio source 1.7*photosphere

elative position not known)

Quiet Sun at 5 GHz: Stephen White.

8.4-GHz observations in 2015 confirm: extended radio coronae are common on active M dwarfs, show diverse structure

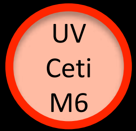
AD Leo



- Resolved in 2 of 3 epochs
- All epochs consistent with quiescent radio source size <= photosphere
- 2 flares in one epoch

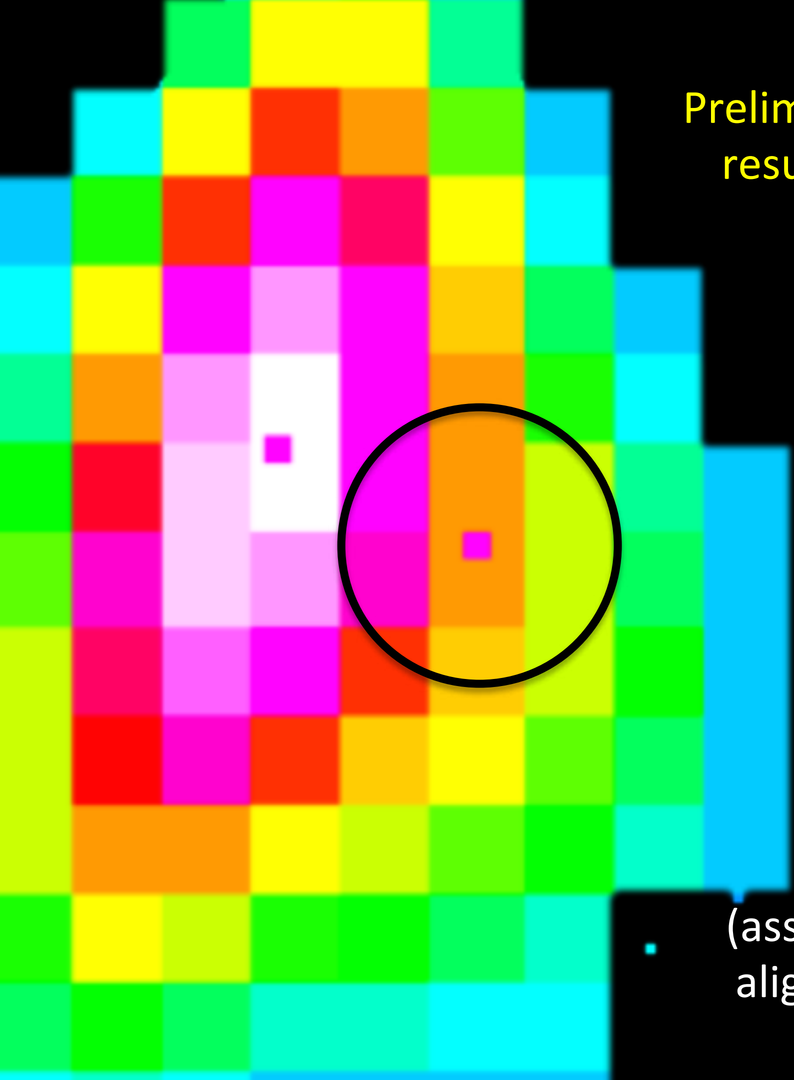
(photosphere physical size shown to scale)

UV Cet

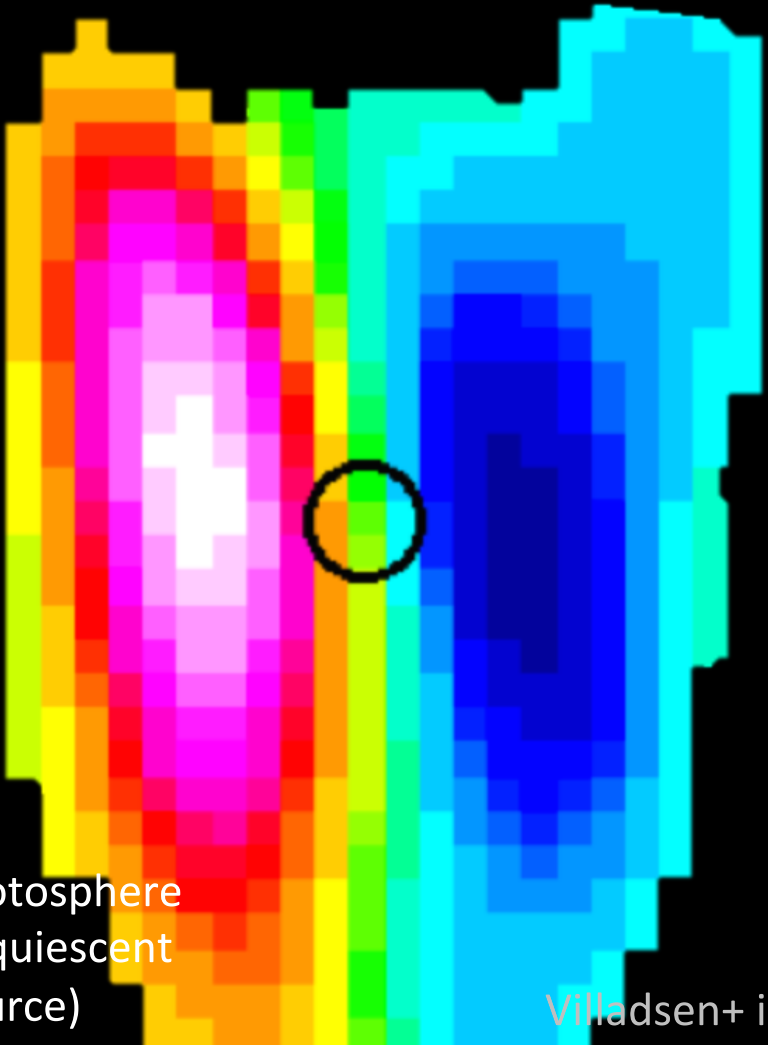


- Resolved in 3 of 3 epochs
- All epochs consistent with quiescent radio source size ~ 3x2 stellar diameters
- 1 auroral coherent burst in each epoch

Villadsen+ in prep

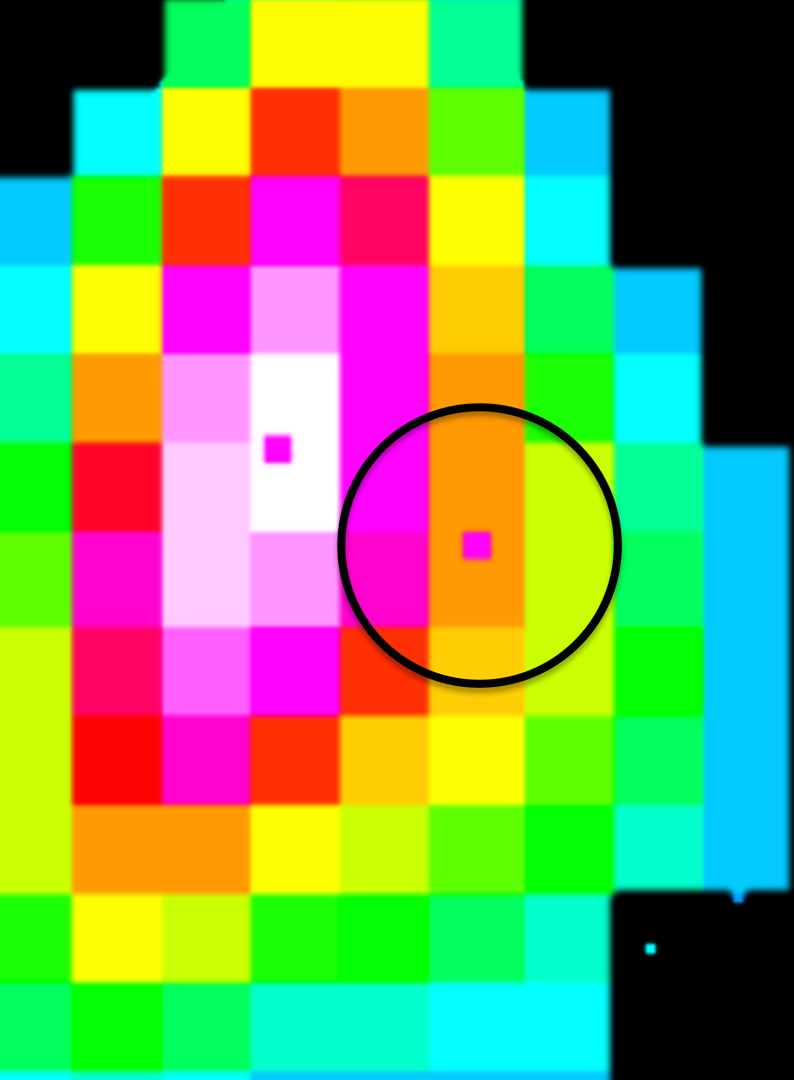


Preliminary results!



(assuming photosphere aligned with quiescent radio source)

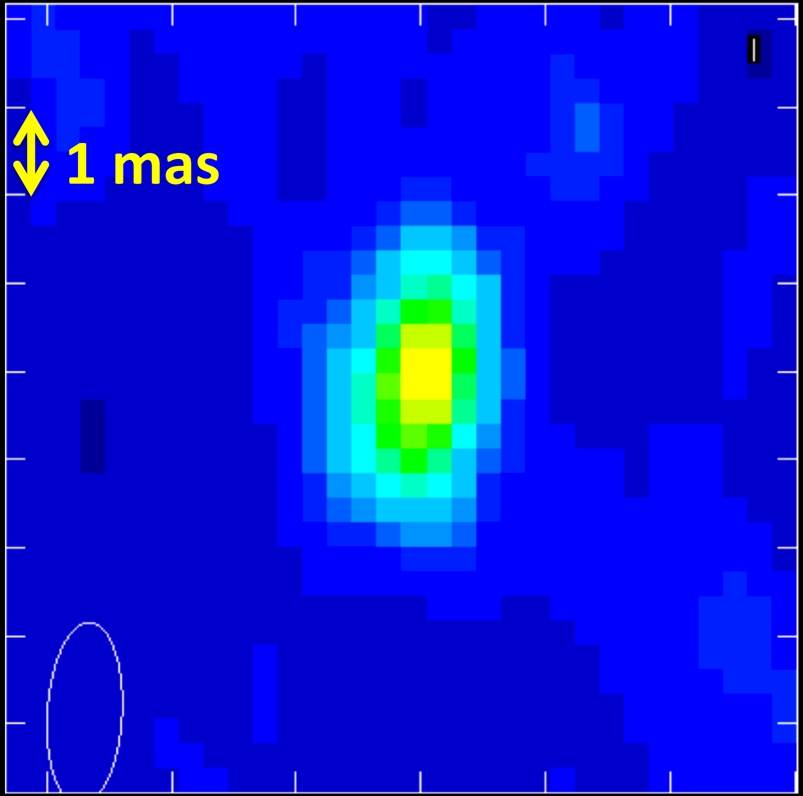
Villadsen+ in prep



AD Leo

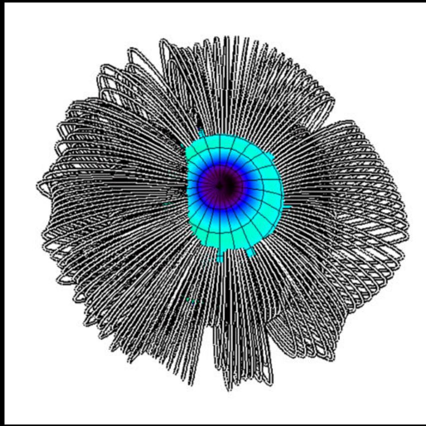
Villadsen+ in prep

VLBA imaging of AD Leo: Two 8.4 GHz flares separated by 0.9 stellar diameters



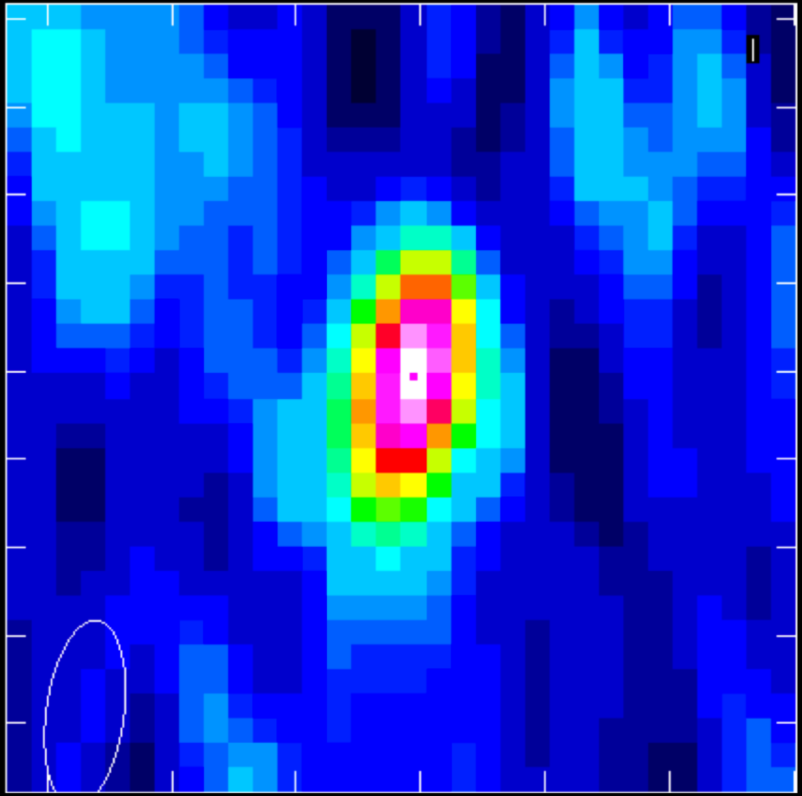
First epoch of coherent storm: 8.4 GHz VLBA quiescent emission is at high levels

Left polarized → south magnetic pole (consistent with ZDI)



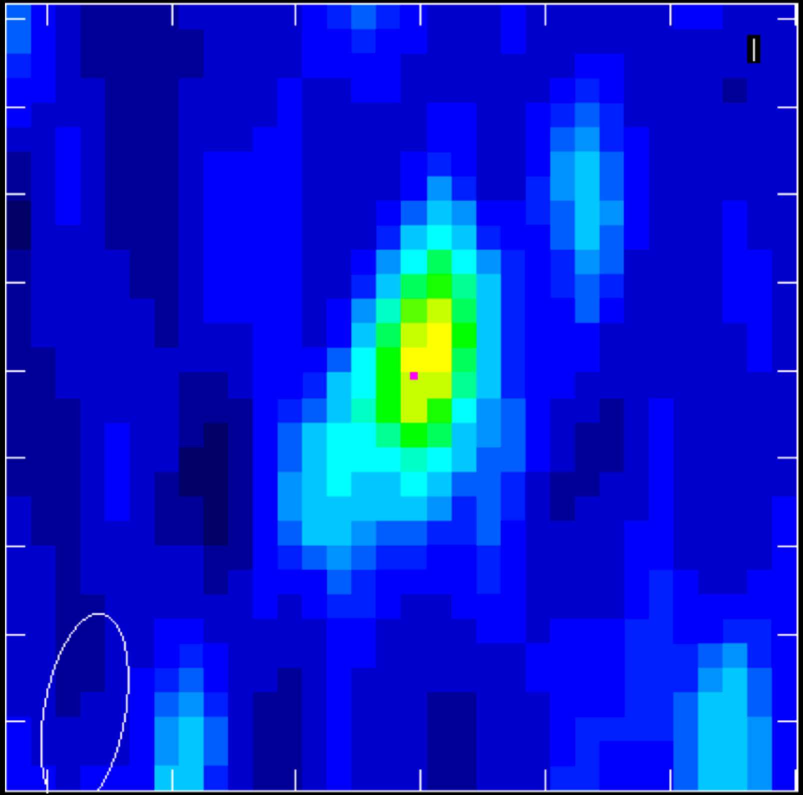
Zeeman Doppler Imaging: Morin+2008, Lang+2014

VLBA imaging of AD Leo: Two 8.4 GHz flares separated by 0.9 stellar diameters



Flare 1: ~ 5 min

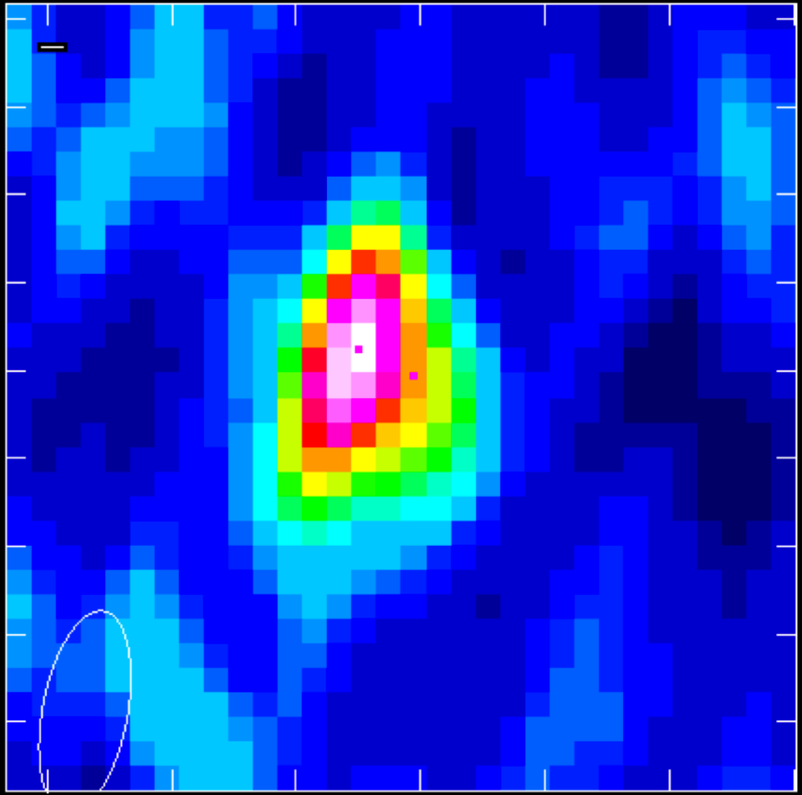
VLBA imaging of AD Leo: Two 8.4 GHz flares separated by 0.9 stellar diameters



Flare 1: ~ 5 min

30 minutes quiet

VLBA imaging of AD Leo: Two 8.4 GHz flares separated by 0.9 stellar diameters

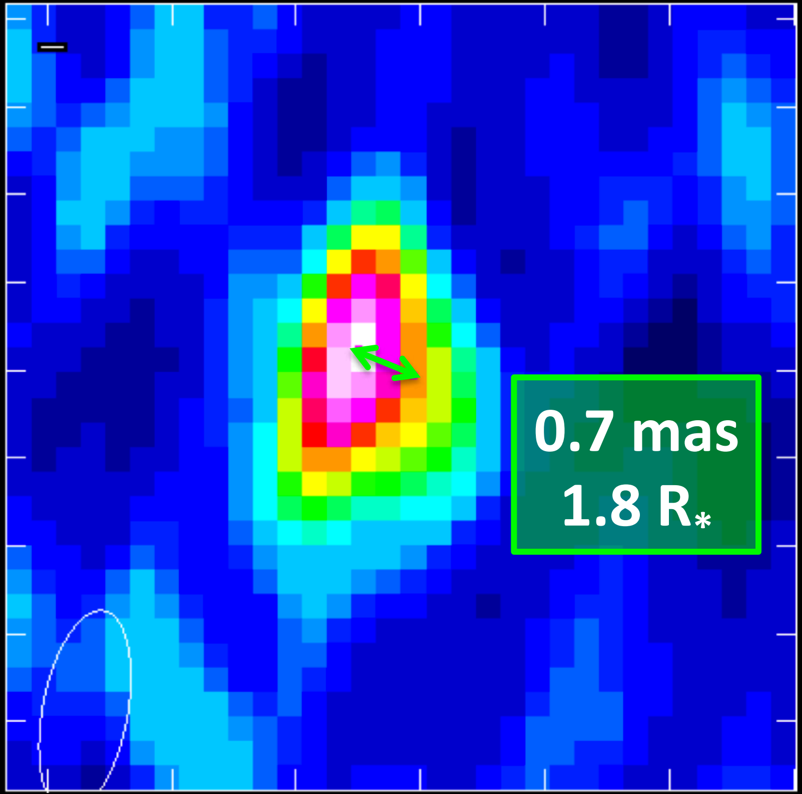


Flare 1: ~ 5 min

30 minutes quiet

Flare 2: ~ 5 min

VLBA imaging of AD Leo: Two 8.4 GHz flares separated by 0.9 stellar diameters



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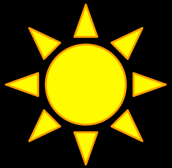
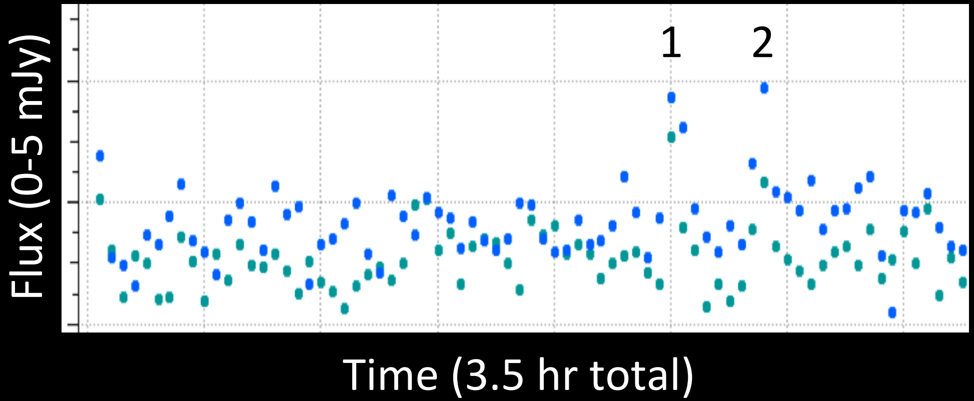
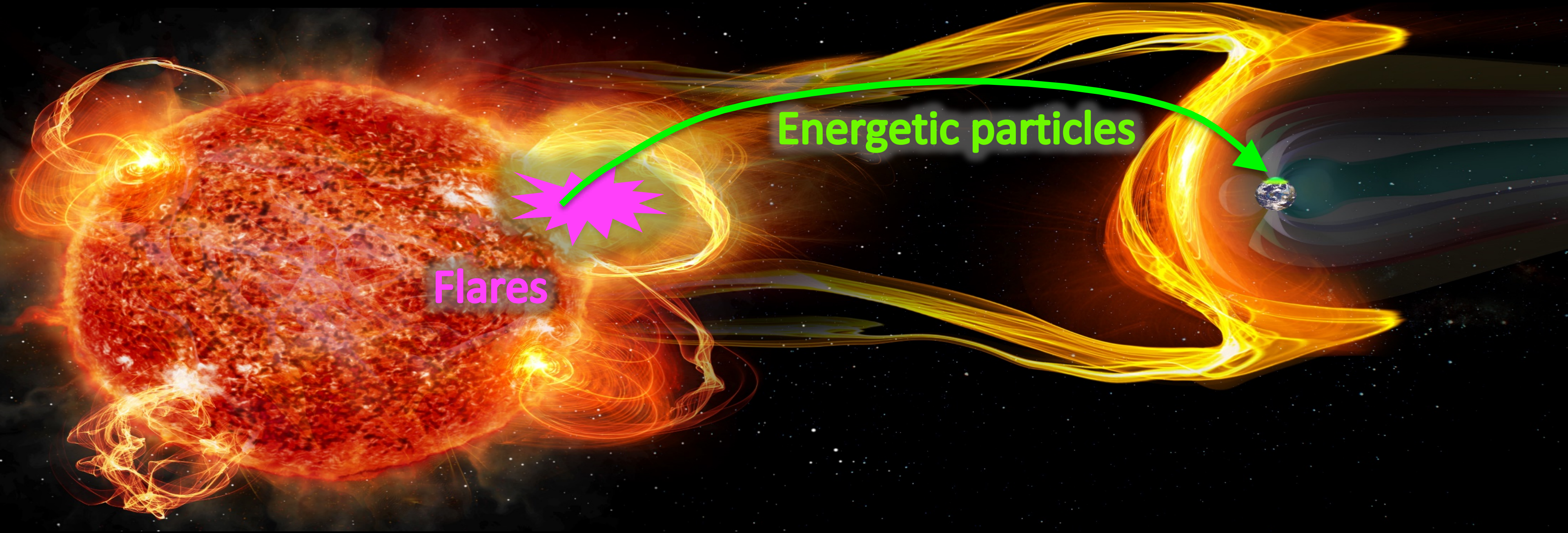


30 minutes quiet

Flare 2: ~ 5 min

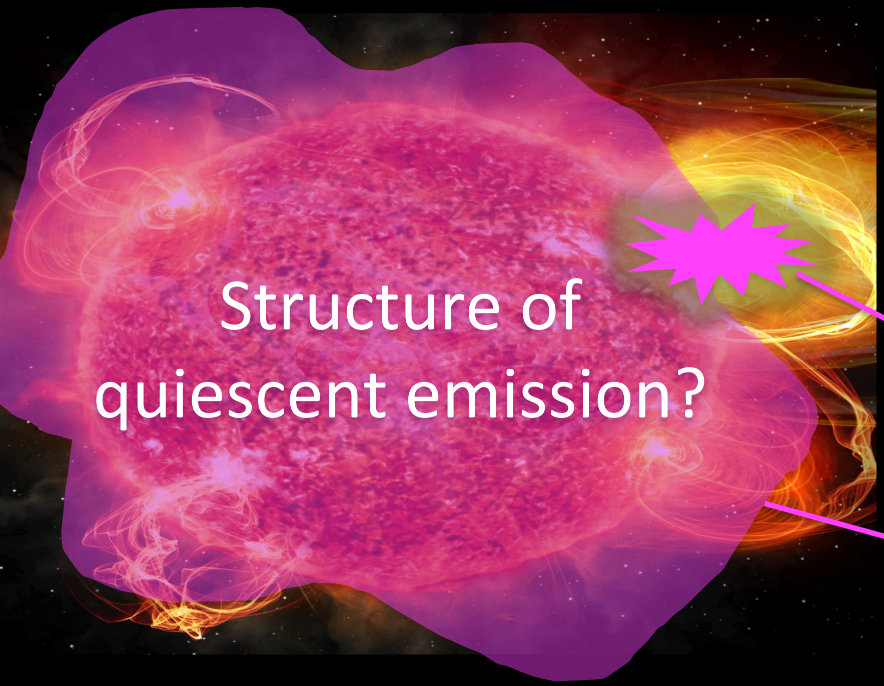


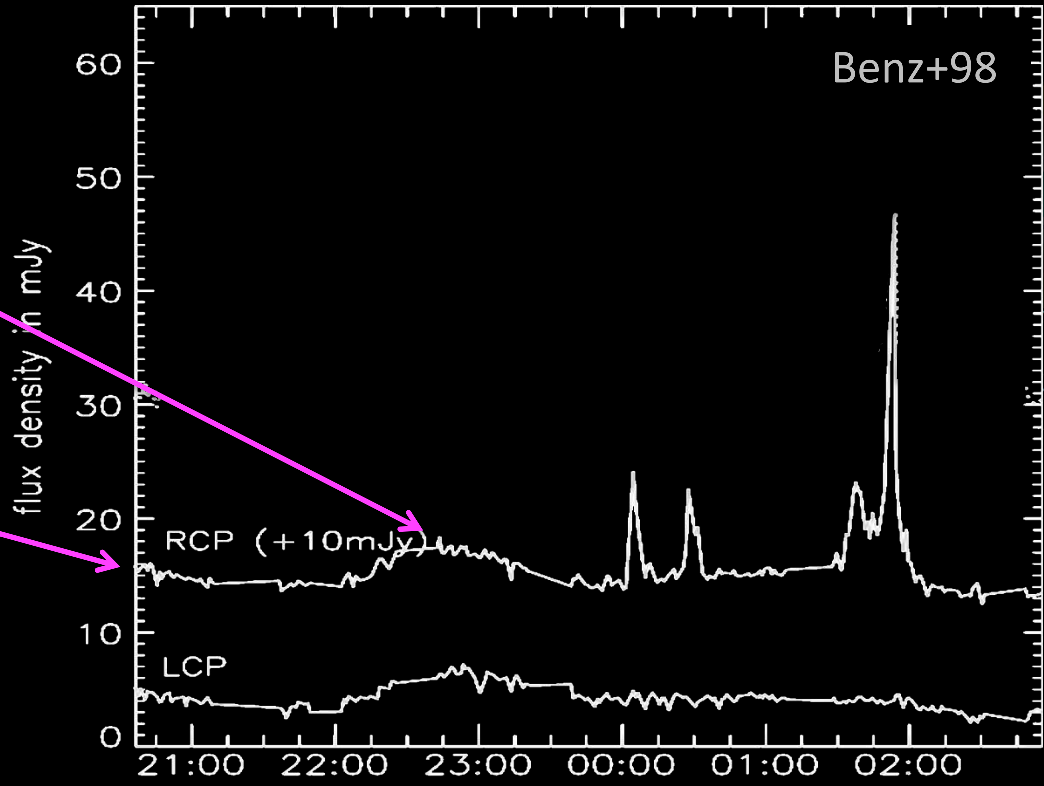
Use this sort of observation to measure radio flare size and position → constrain flare particle acceleration



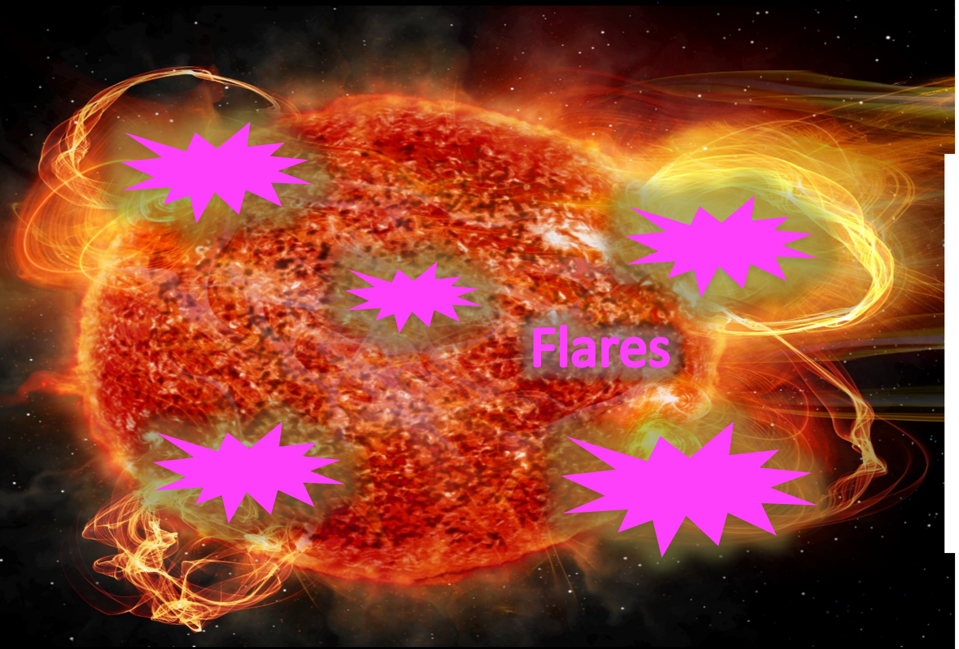
However, active stars also produce quiescent gyrosynchrotron emission, whereas solar gyrosynchrotron emission is only seen in flares

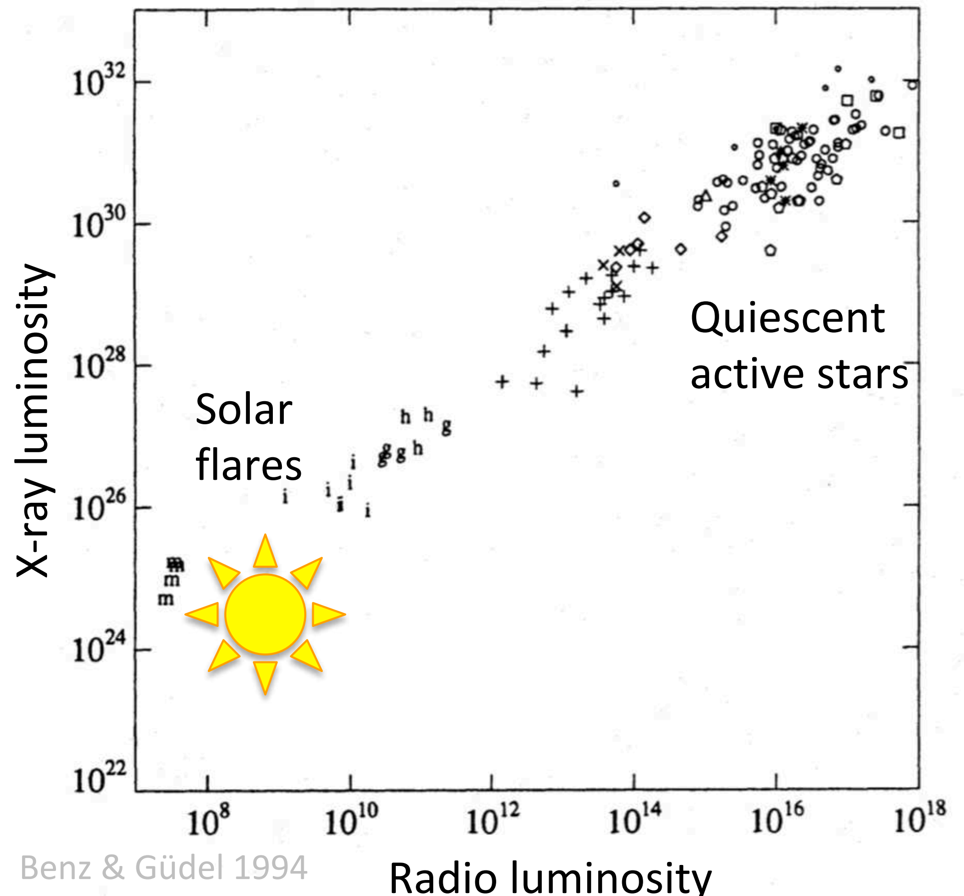
Active stars also produce quiescent gyrosynchrotron emission, whereas the Sun only produces gyrosynchrotron in flares



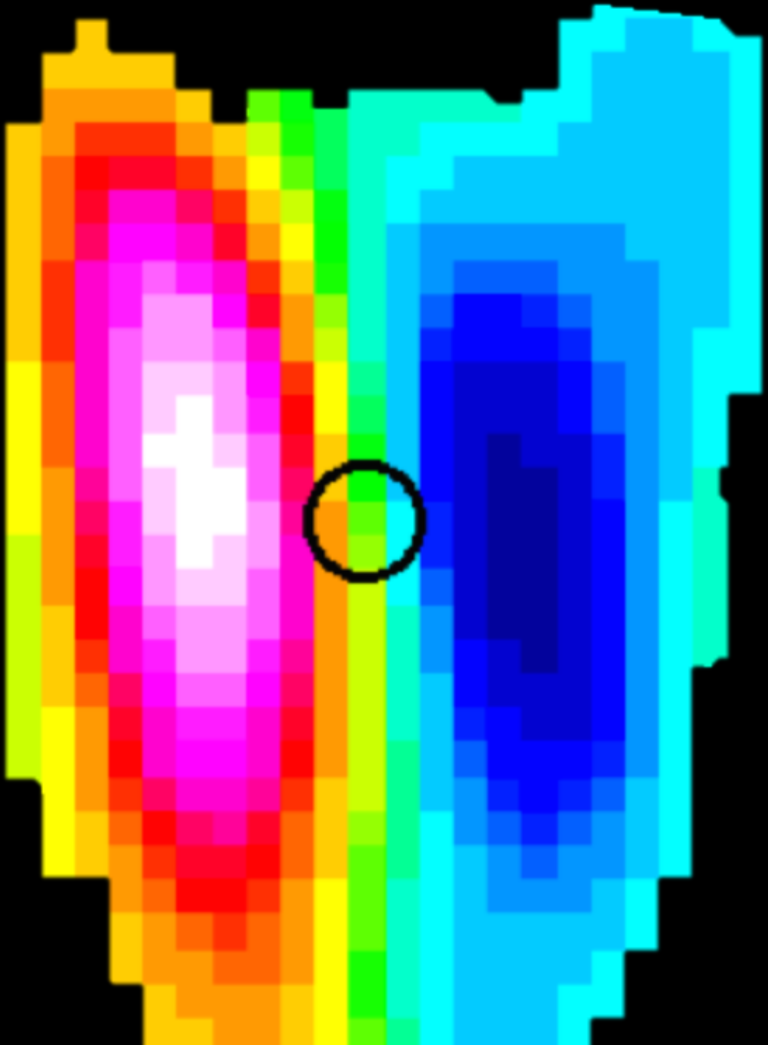


The current best understanding is that the quiescent emission is a sum of small flares

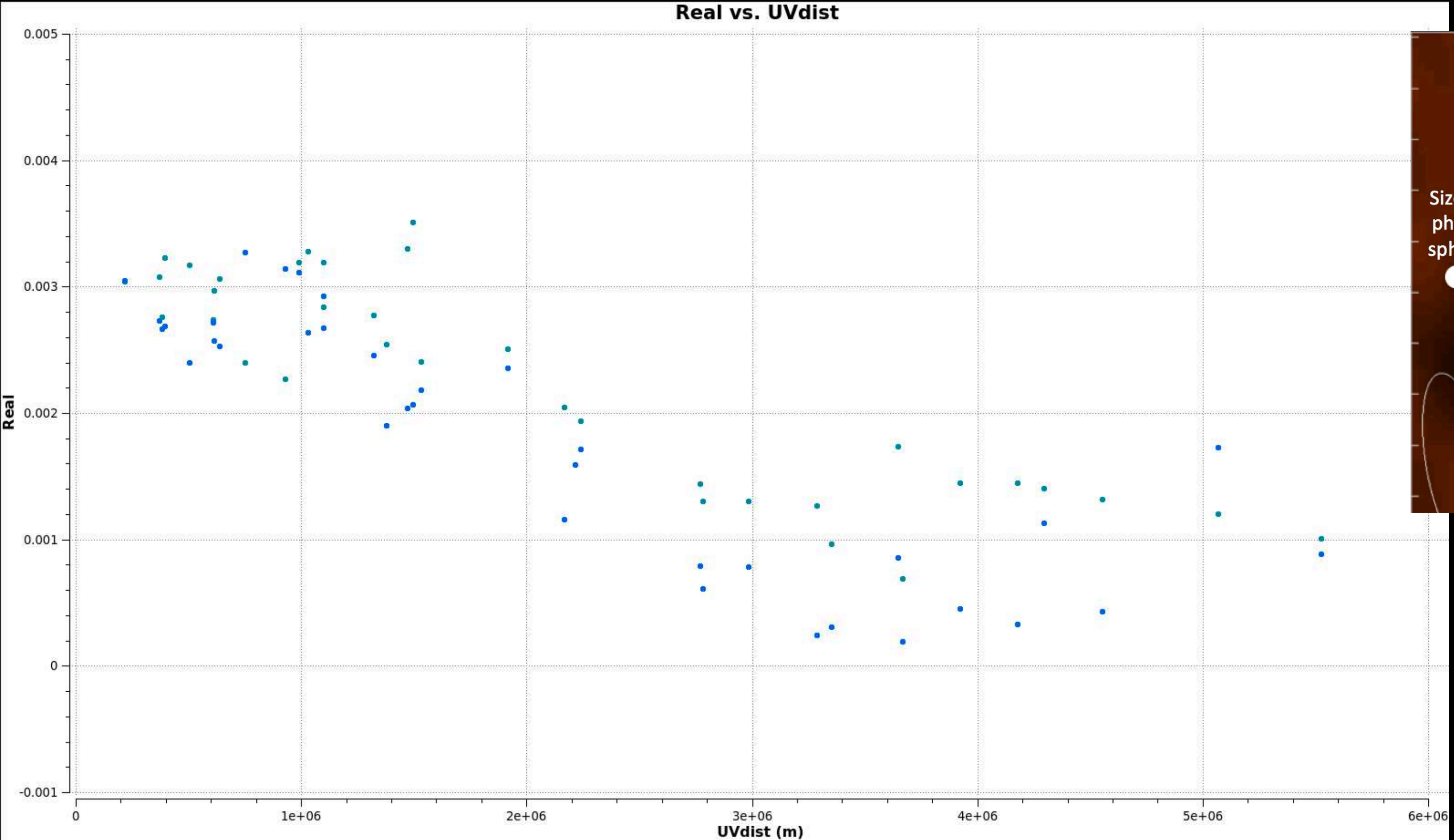


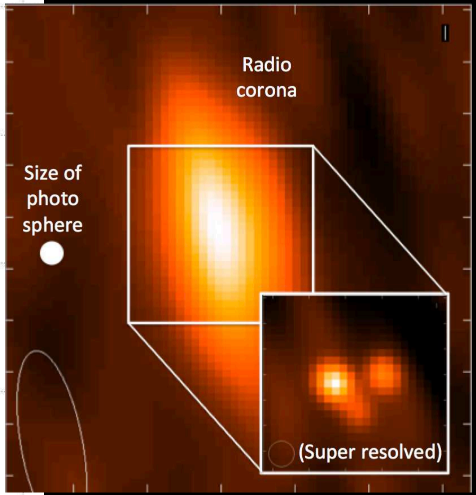


UV Cet



UV Ceti has an extended radio source - size measured by fitting elliptical Gaussian to uv data





~3x2 stellar diameters in all epochs (+/- 0.2-0.7 diameters), more extended in N-S dir

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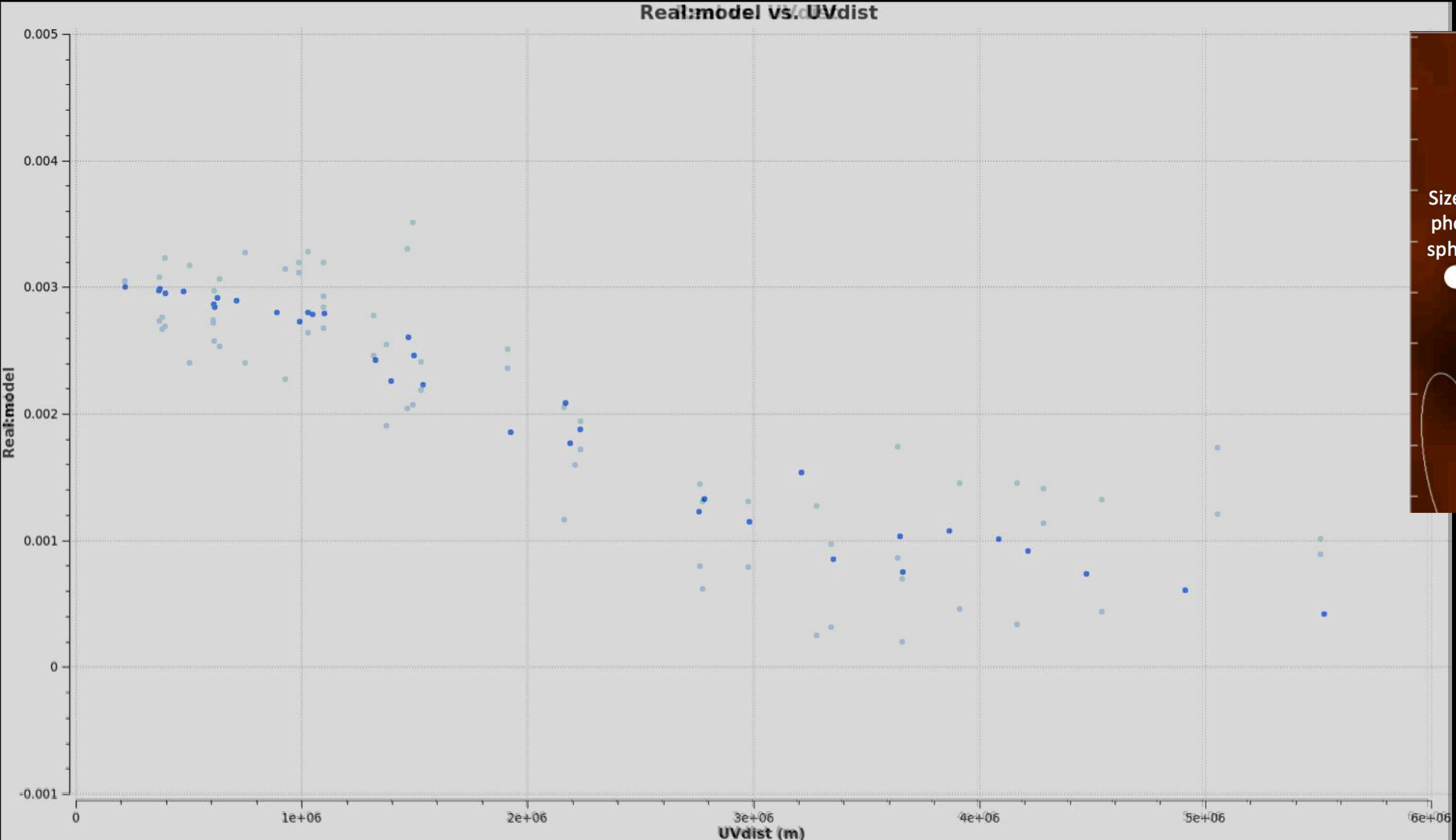
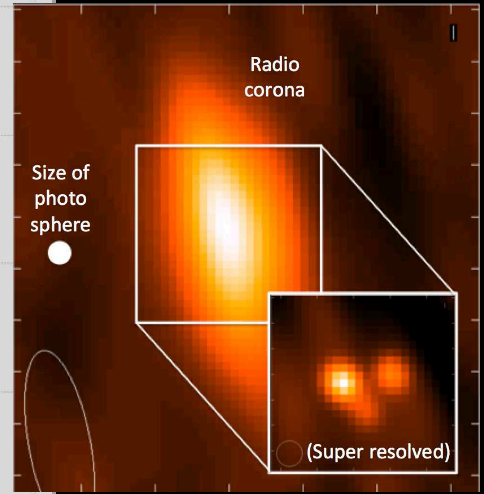




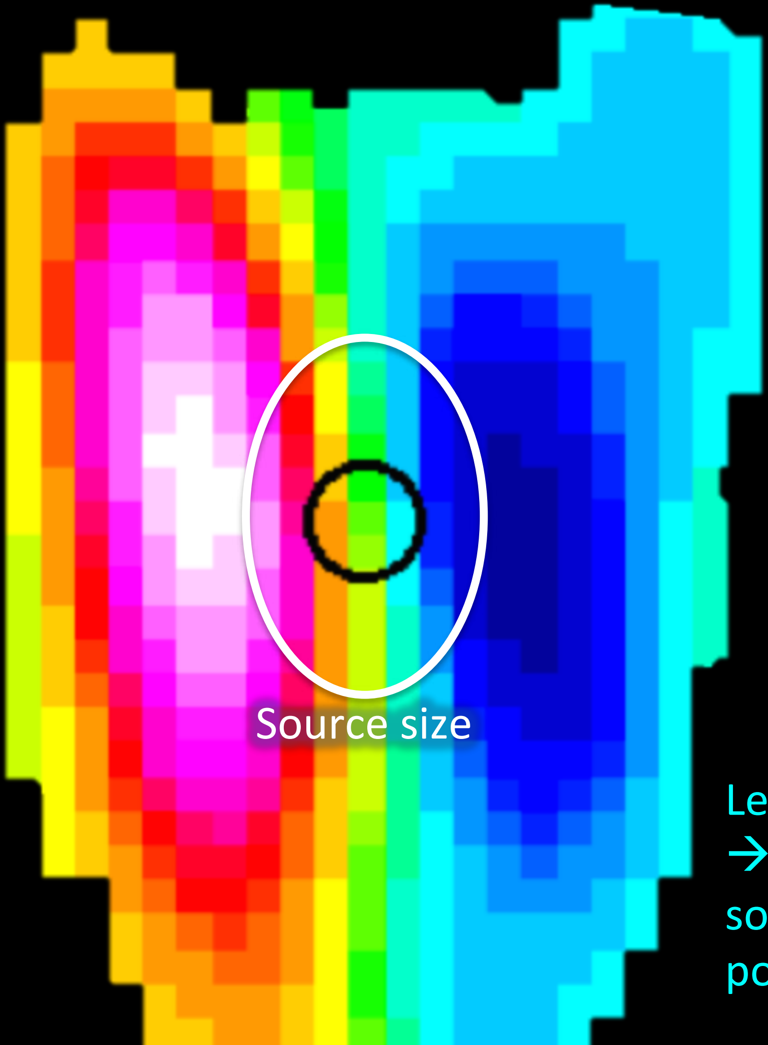
~3x2 stellar diameters in all epochs (+/- 0.2-0.7 diameters), more extended in N-S dir

UV Cet: Extended emission from dipole field?

Apparent magnetic dipole seen in two epochs, consistent structure

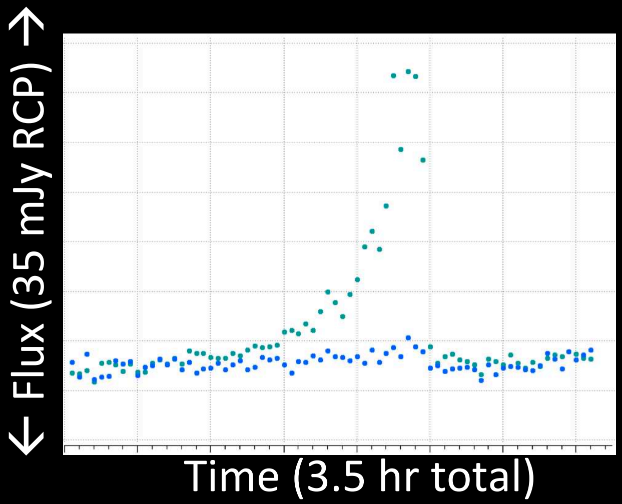
→ Radio emission associated with large-scale magnetospheric processes?

Structure does not meet expectation for “sum of small flares” scenario

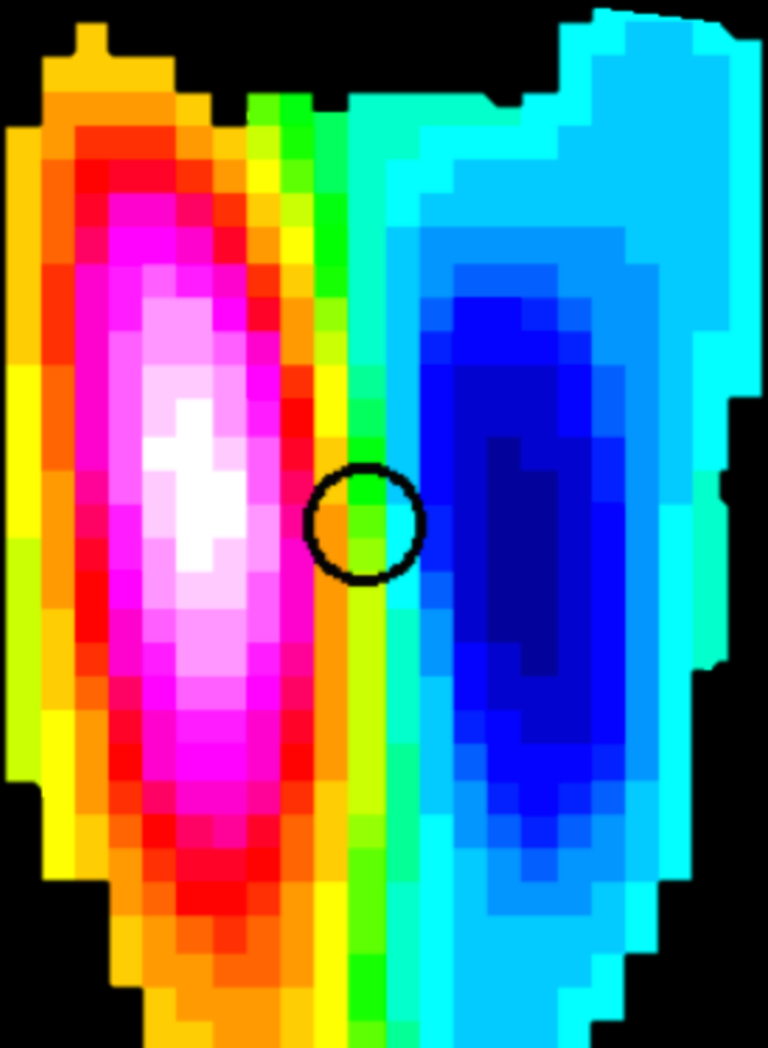


UV Cet: Coherent bursts

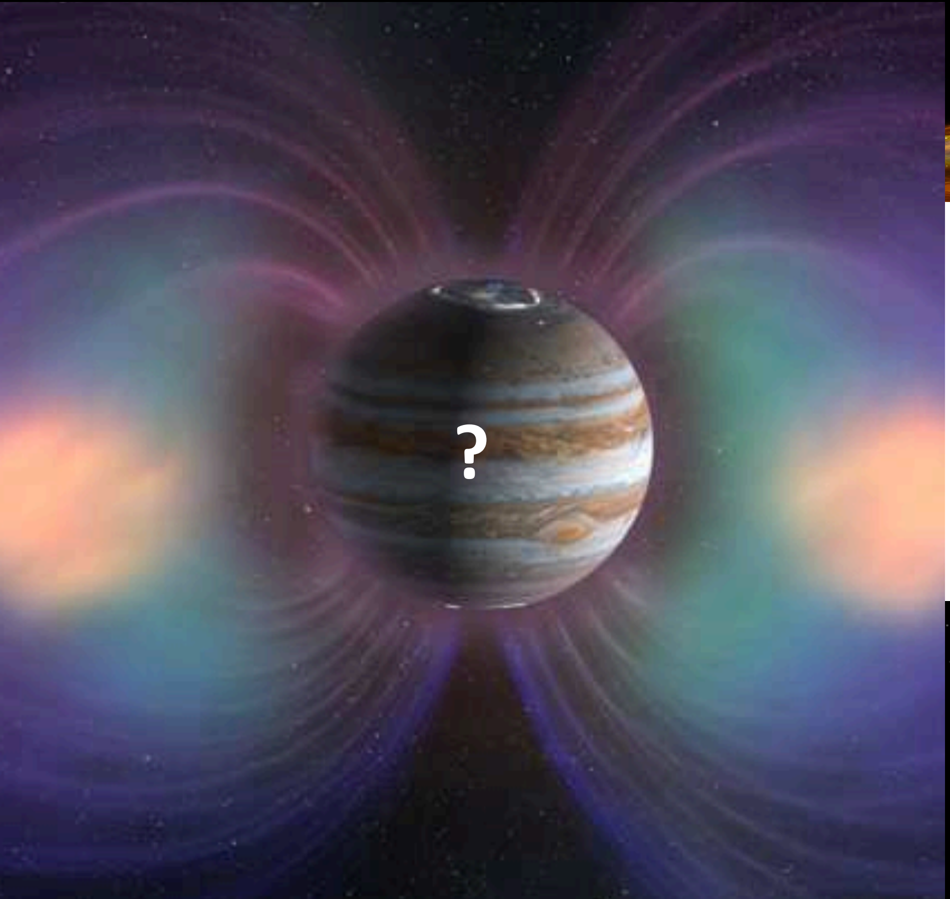
Radio aurora: periodic coherent bursts (>10 mJy) seen in all 3 epochs, consistent with point source

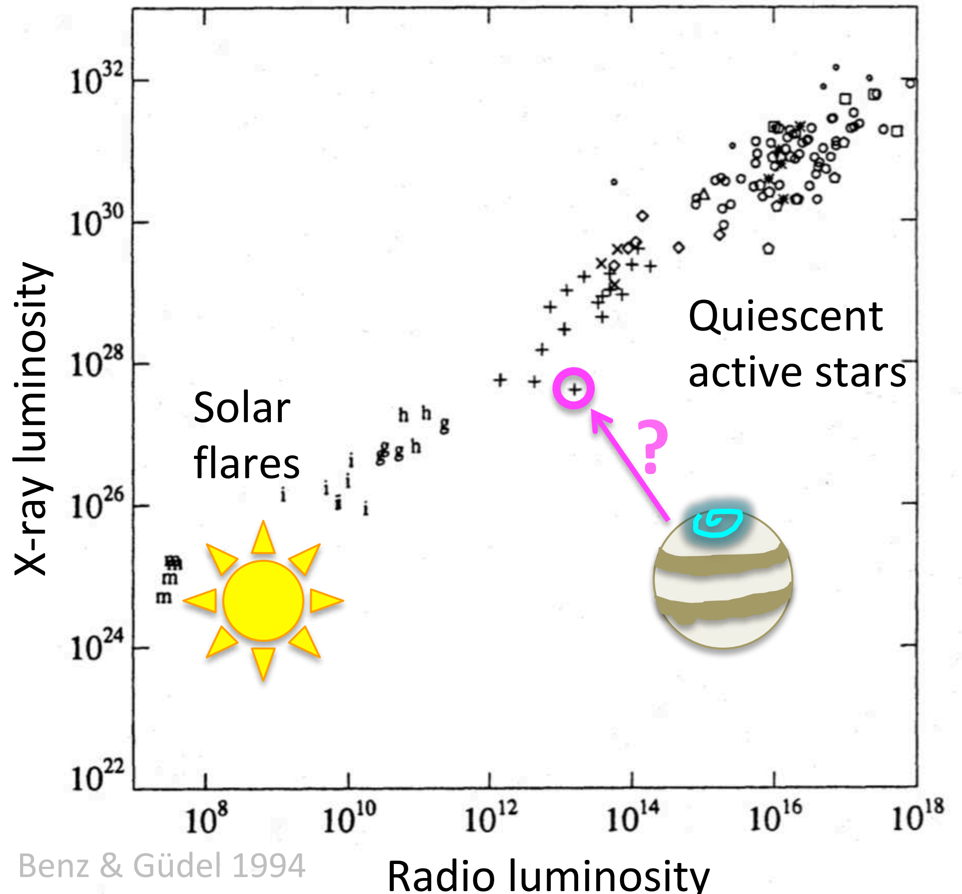


Unable to localize coherent bursts due to lack of astrometric-quality phase calibration (future work!)



UV Ceti's radio emission, overluminous by x10, may be due to global magnetospheric processes linked to its aurora

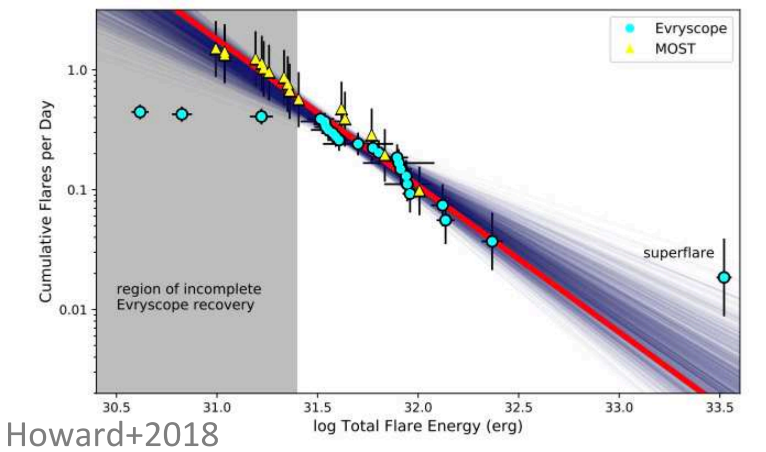


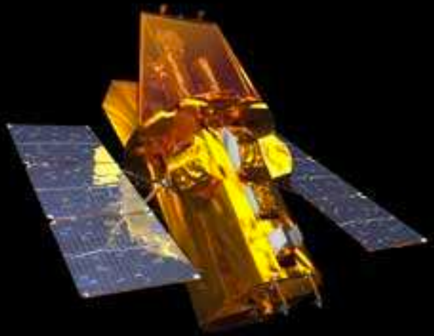


Why observe stellar activity with VLBI?

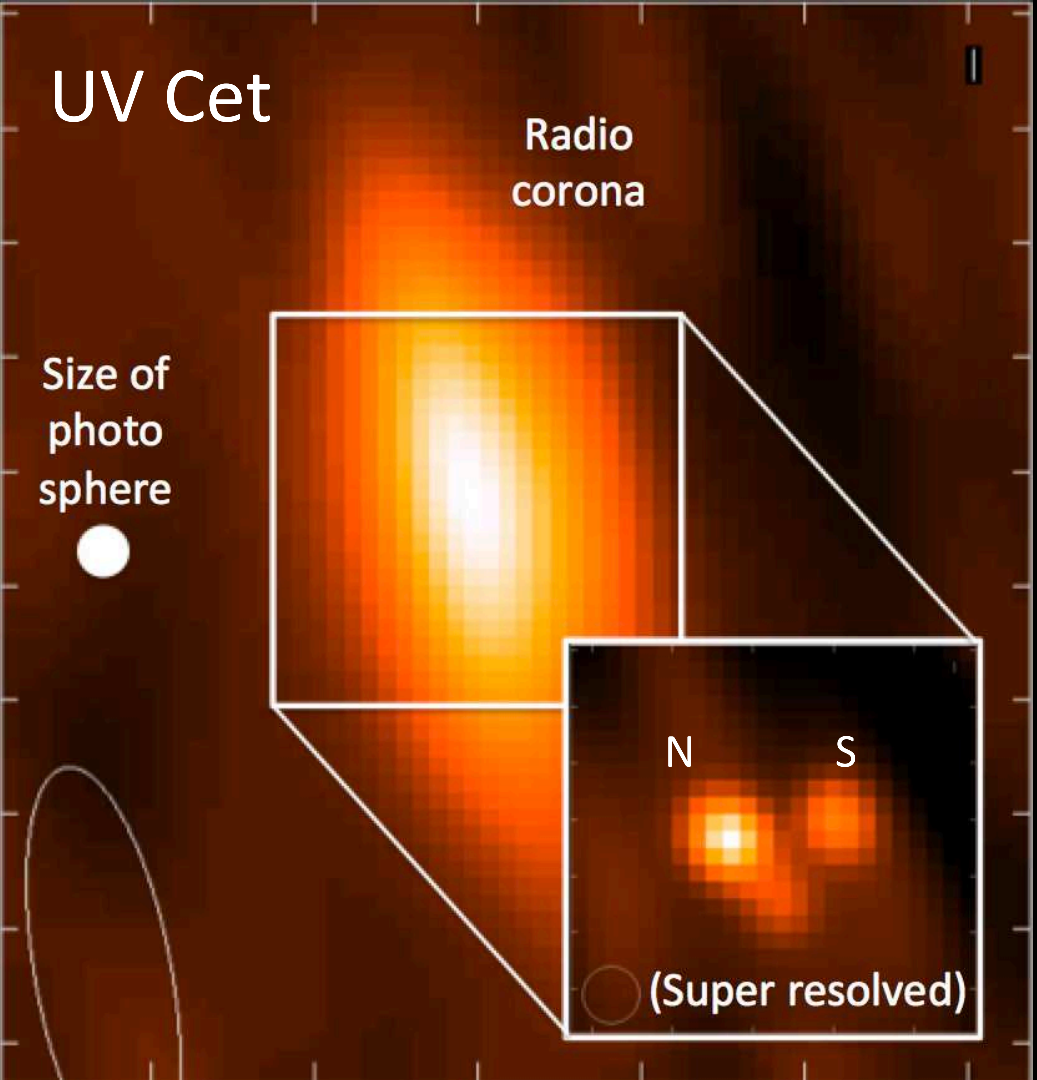
- Imaging
  - Radio sources trace closed magnetic structures and high densities
    - Measure sizes
    - Imaging helps choose appropriate model
    - Imaging polarization structure reveals length scale of magnetic loops
- Astrometry
  - Distances
  - Find companions
  - Track transient or variable features
  - Locate radio source relative to photospheric magnetic field

Superflares with a Flexible VLBI Network





Superflares, occurring every few months to years, should have an especially dramatic impact for habitability. VLBI observations within minutes to hours would enable measurement of the radio flare structure and size, providing data on flare particle acceleration.



Questions?

- Thanks to: Workshop organizers and participants, Tim Bastian, Gregg Hallinan, Amy Mioduszewski, Stephen Bourke

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