Radio emission from (low-mass) young stellar objects

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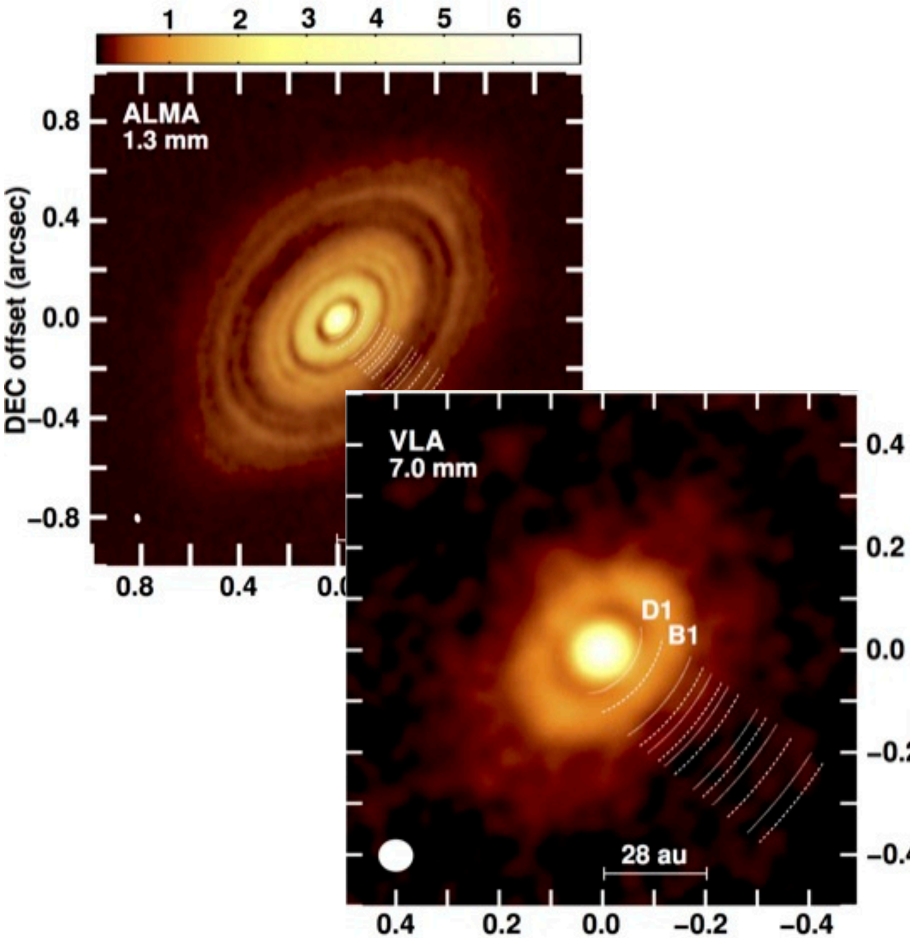
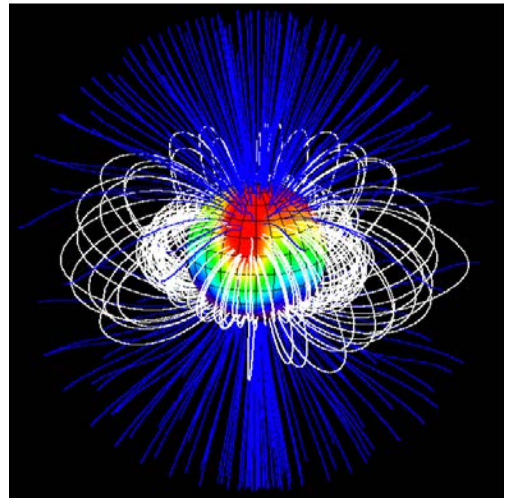
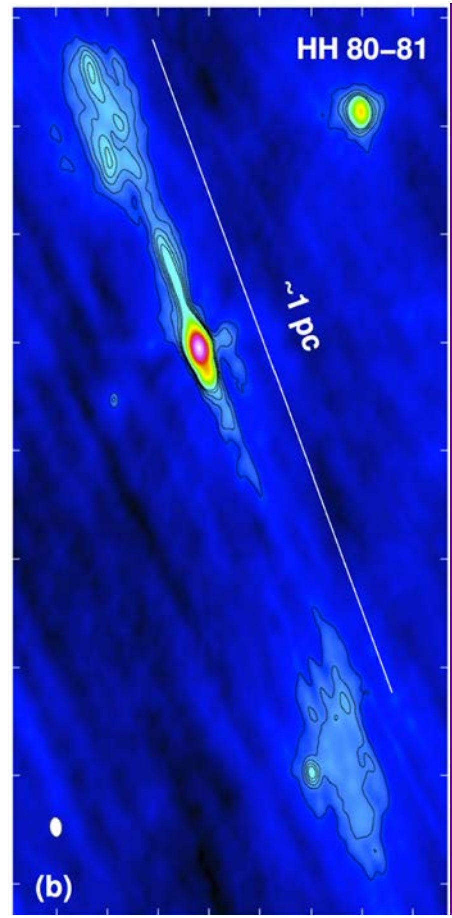
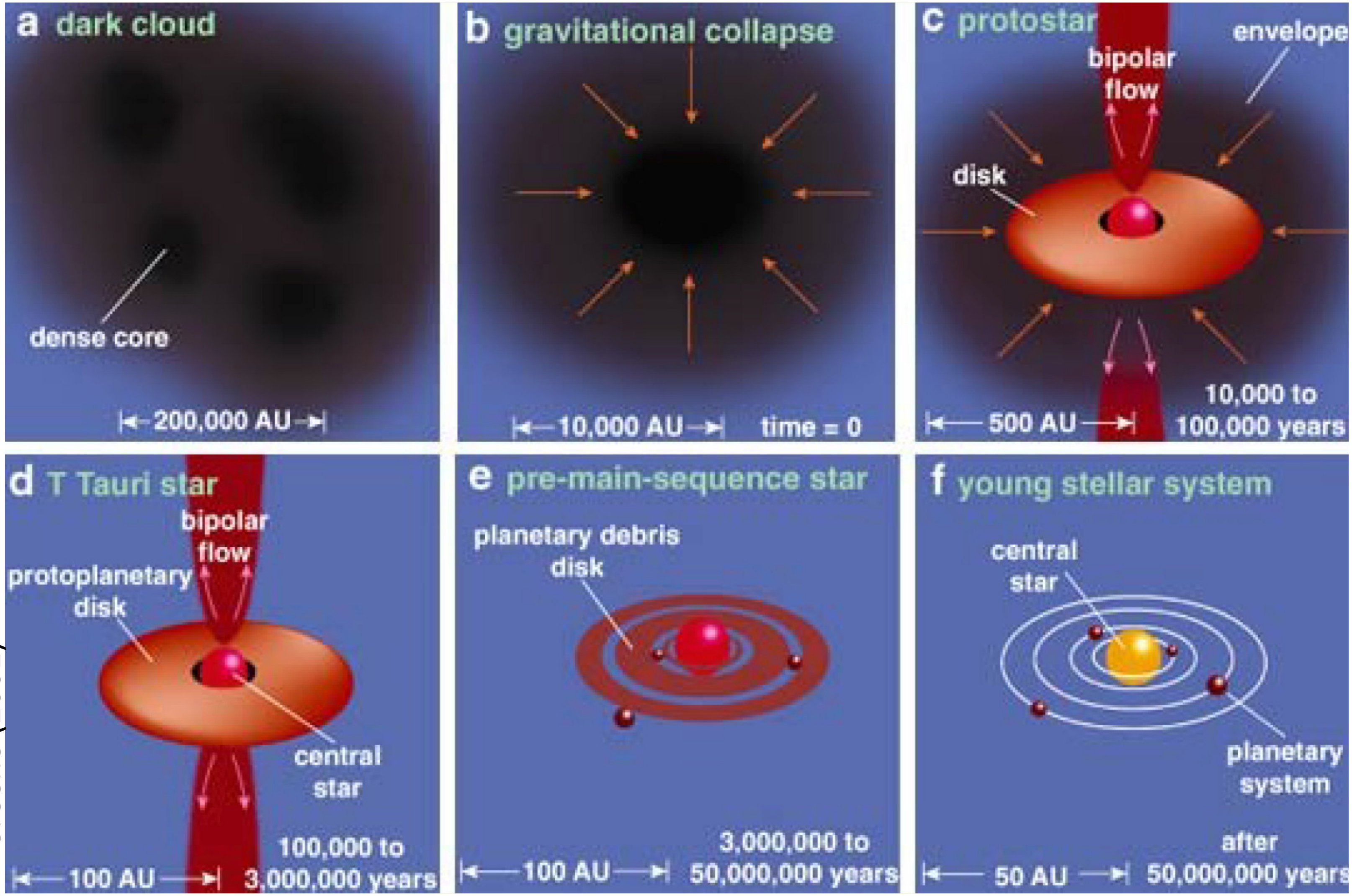






Scope of the talk

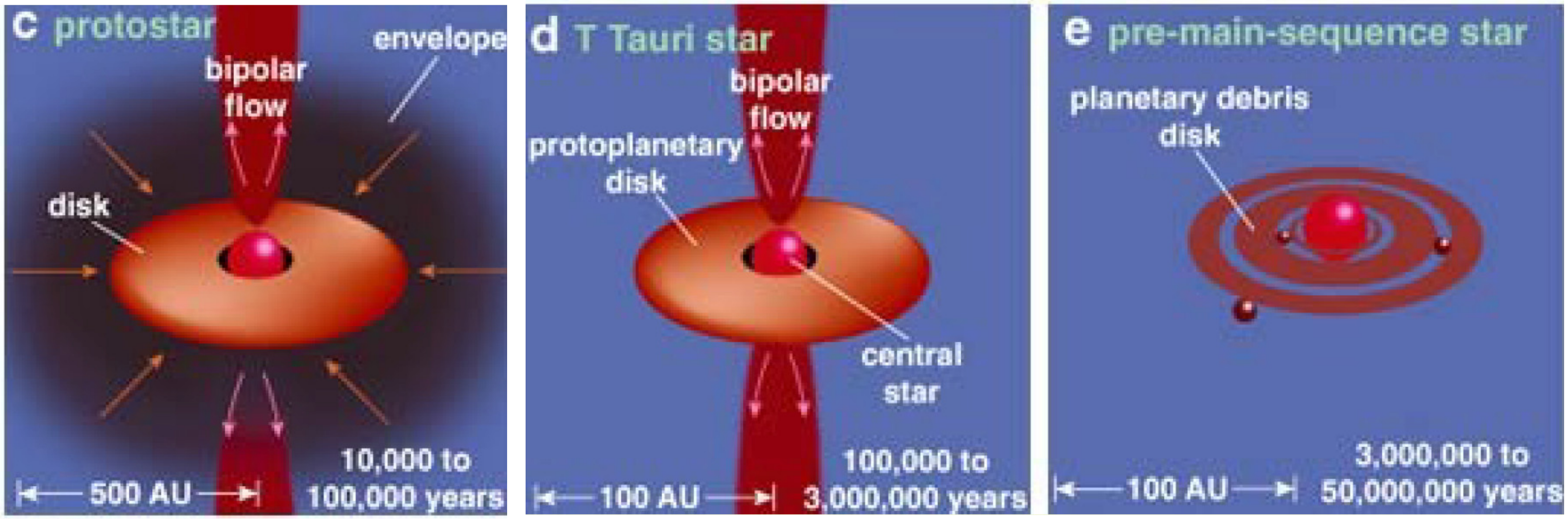
- ❑ Continuum radio emission ($\lambda > 1$ cm)
- ❑ Young stars ($\tau < 50$ Myr)
- ❑ Low-mass ($M < 5\ M_{\odot}$)



Greene (2001)

Scope of the talk

- ❑ Radio emission (λ > 1 cm)
- ❑ Young stars (τ < 50 Myr)
- ❑ Low-mass ($M < 5\ M_{\odot}$)



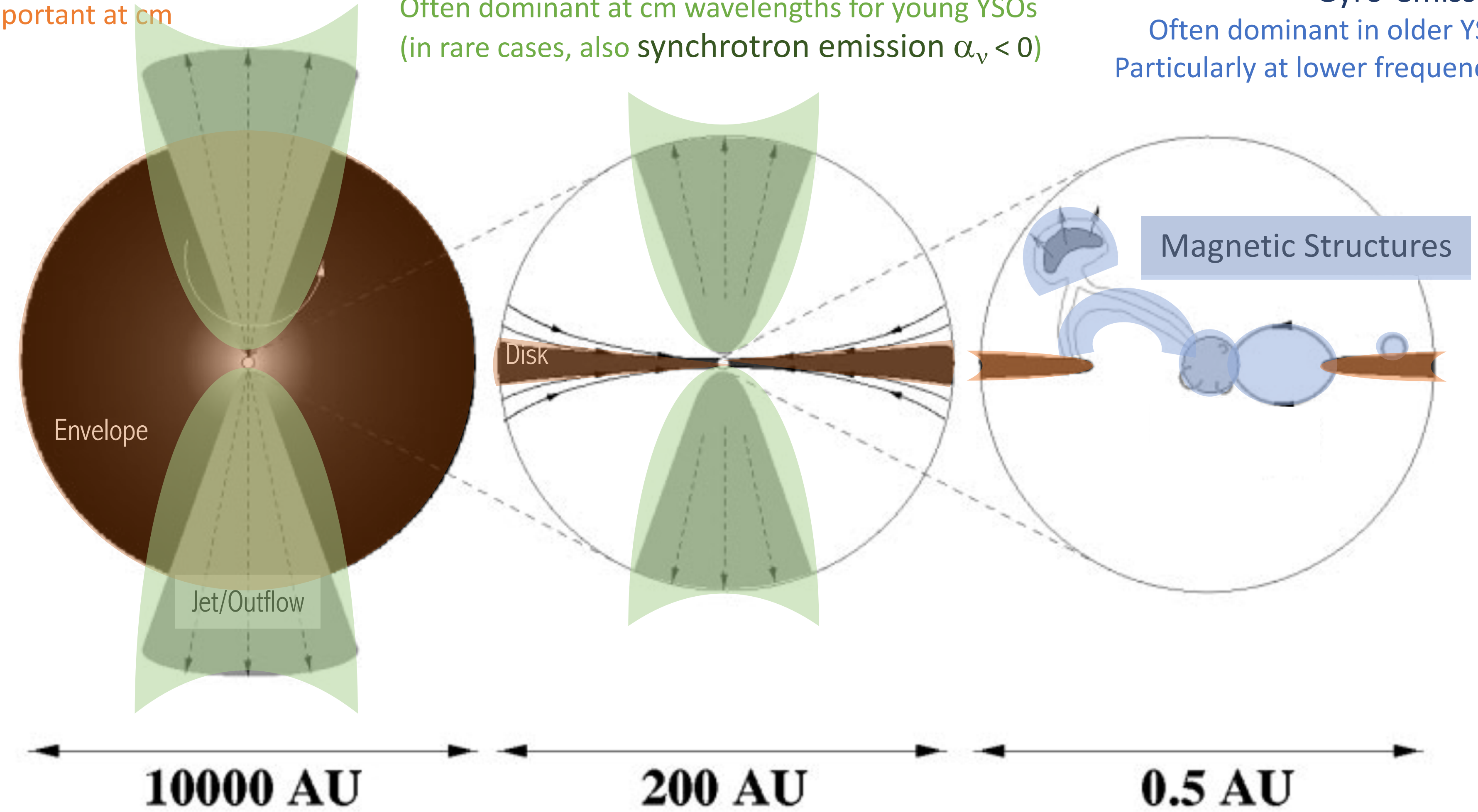
Greene (2001)

Origin of radio emission

Envelope and Disk are dusty structures
Thermal Dust emission ; $\alpha_\nu > 2$
Dominant at mm/submm
Often still important at cm

Jets and outflows are (partially) ionized structures
Thermal Bremsstrahlung emission ; $-0.1 < \alpha_\nu < 2$
Often dominant at cm wavelengths for young YSOs
(in rare cases, also synchrotron emission $\alpha_\nu < 0$)

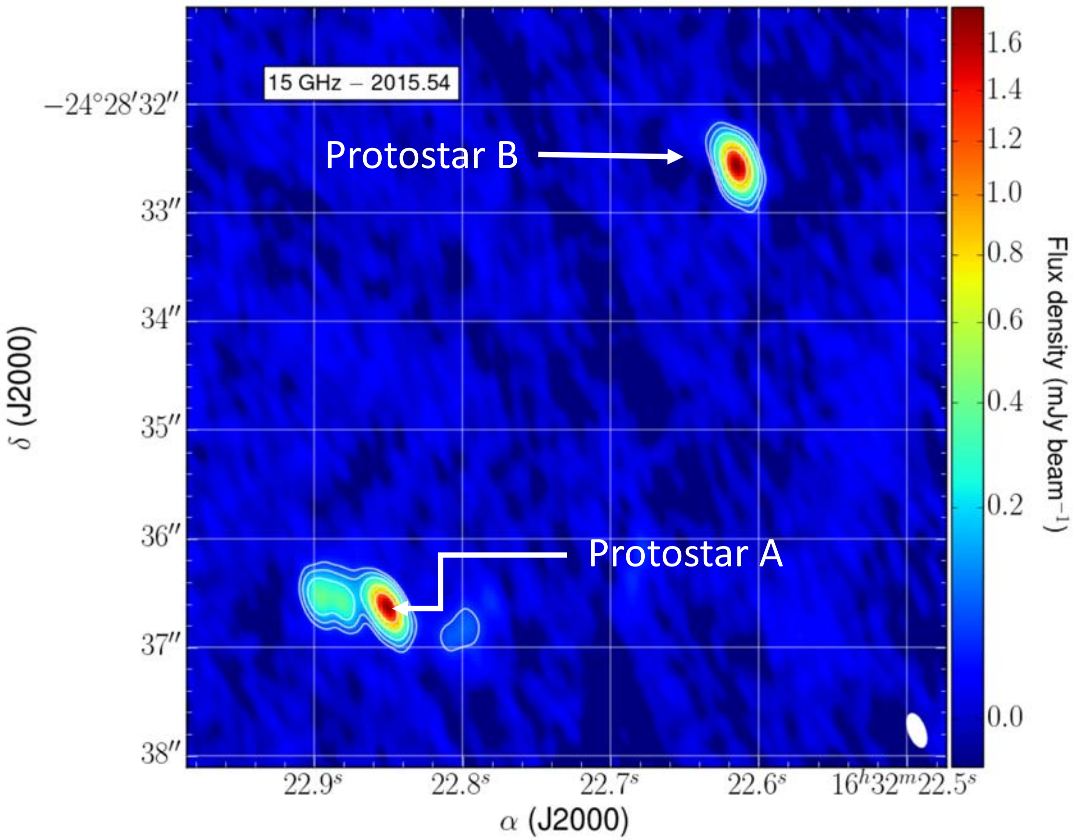
Magnetic structures
Gyro-emission
Often dominant in older YSOs
Particularly at lower frequencies

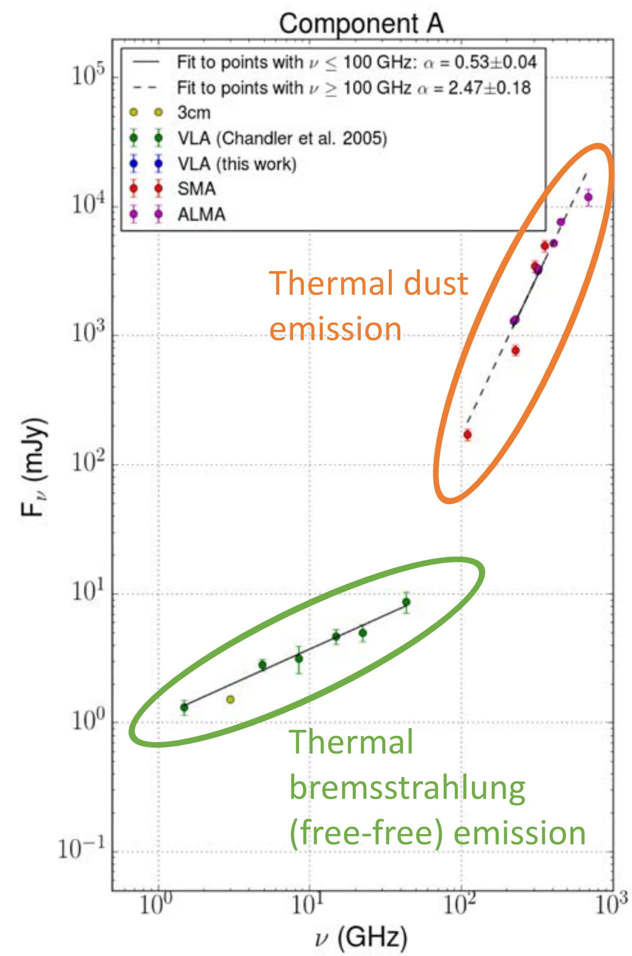


Adapted from Feigelson & Montmerle (1999)

Typical SED of a younger YSO (Class 0/I/FS)

IRAS 16293—2422 (Class 0 binary protostar in the ρ-Ophiuchi molecular complex)

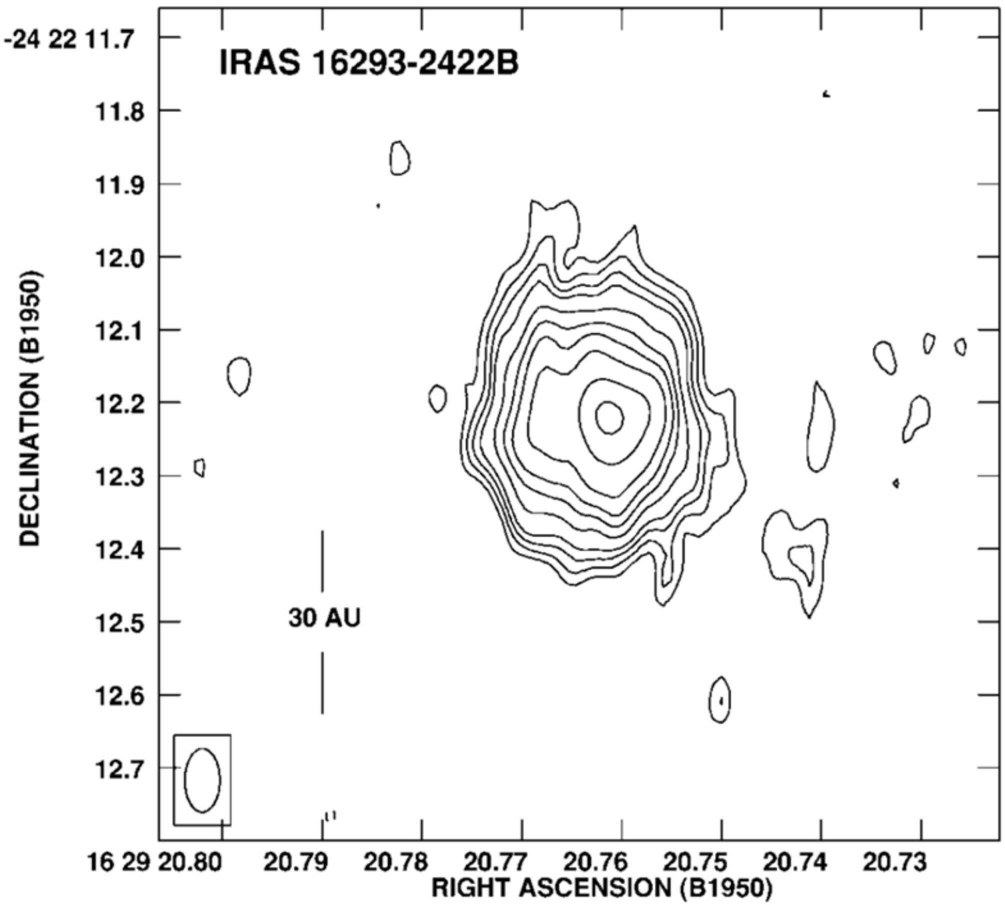


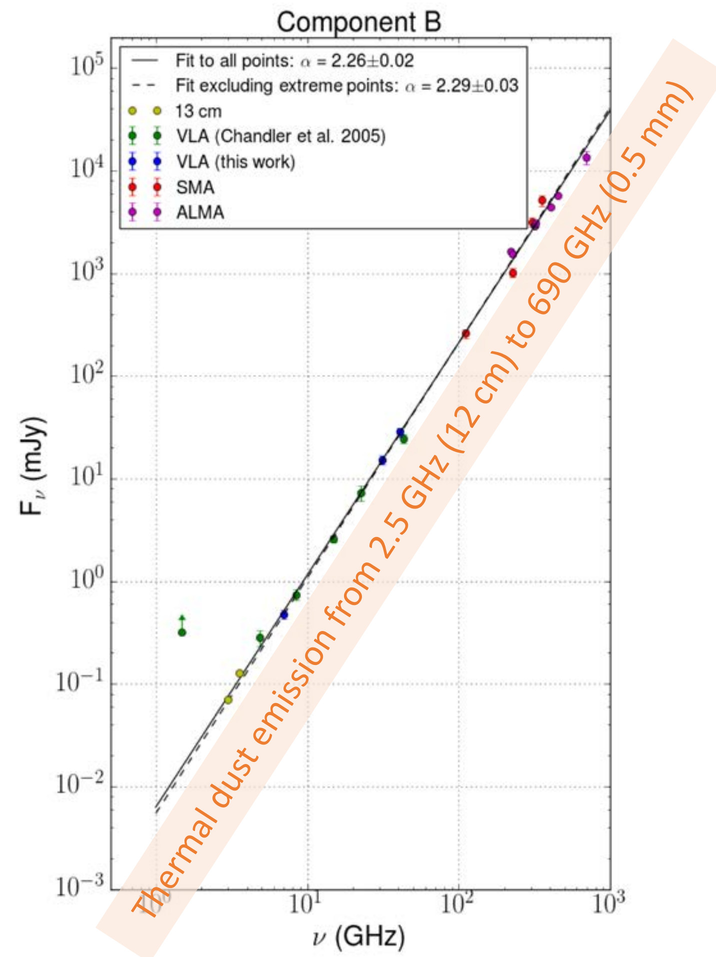


Rodríguez et al. (2005)
Chandler et al. (2005)
Hernandez et al. (2017)

The unusual case of IRAS 16293—2422

IRAS 16293—2422 (Class 0 binary protostar in the ρ-Ophiuchi molecular complex)





Rodríguez et al. (2005)
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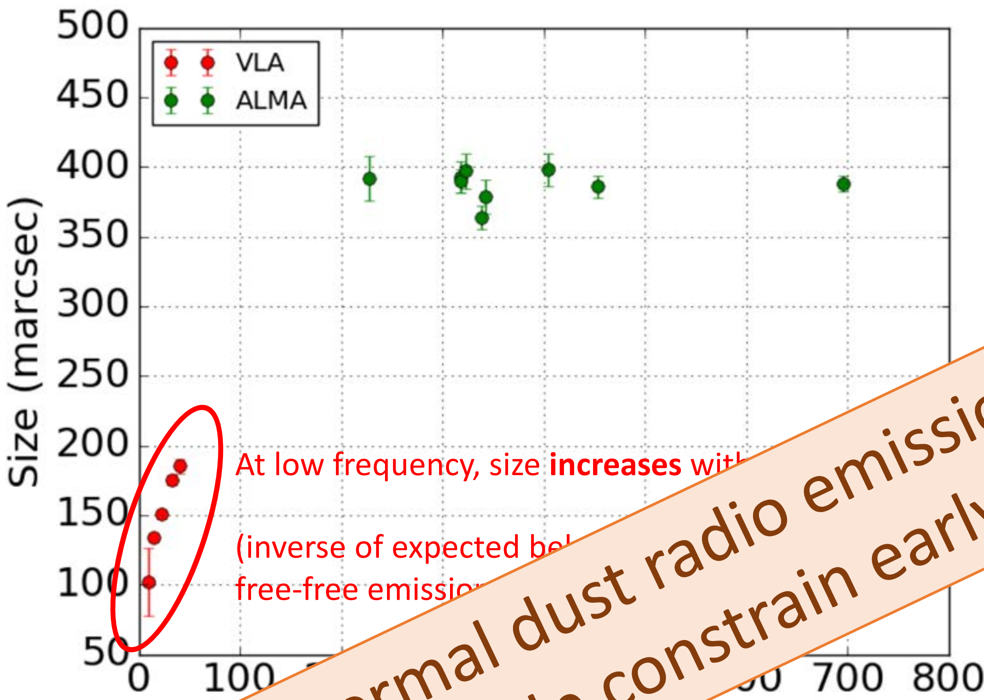
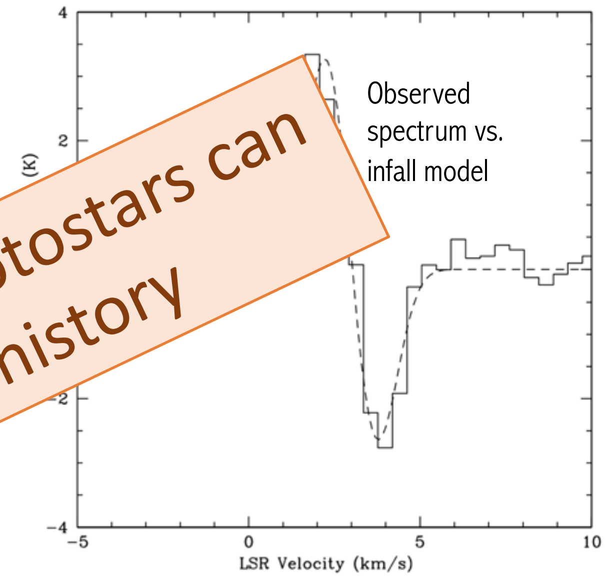
The unusual case of IRAS 16293–2422

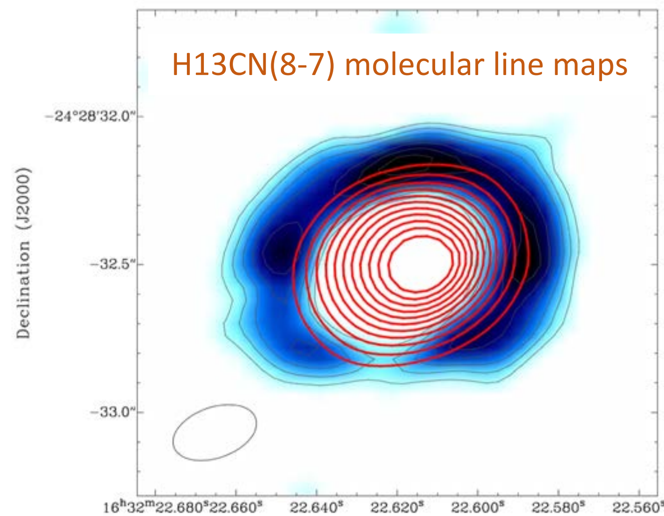


H13CN(8-7) molecular line profile



Thermal dust radio emission from protostars can help constrain early accretion history

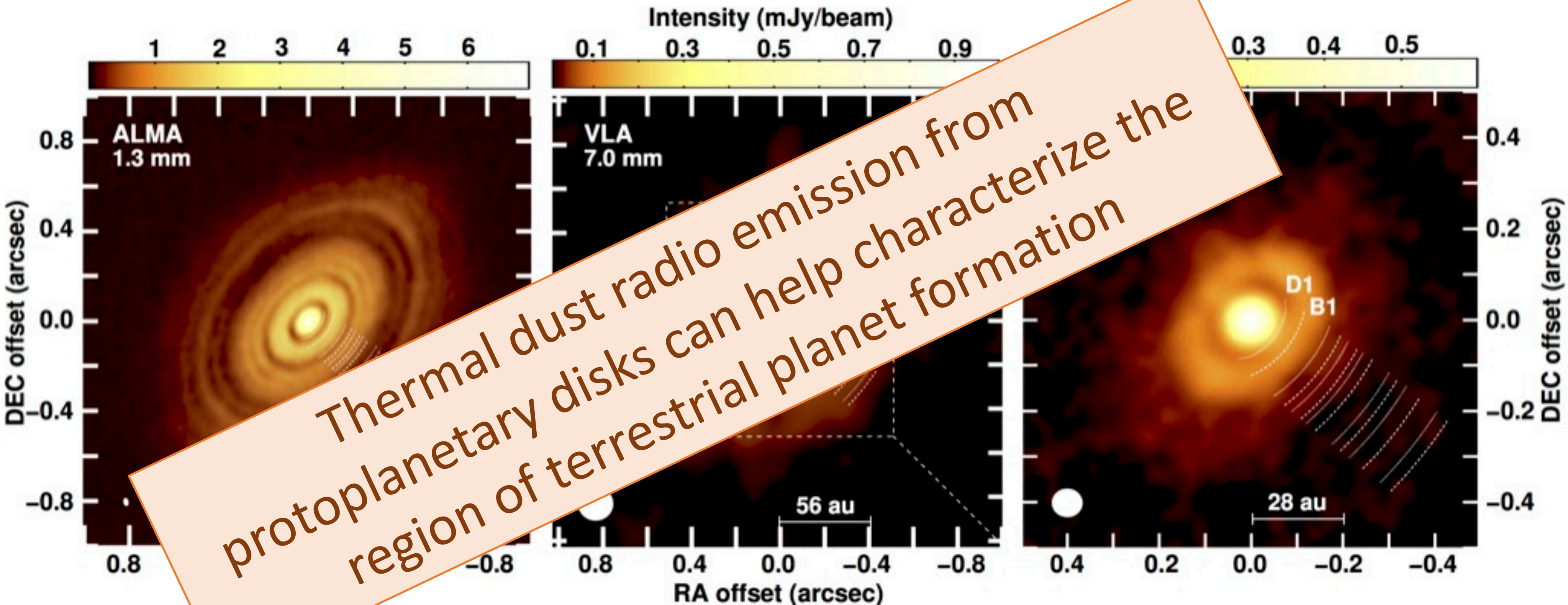
H13CN(8-7) molecular line maps



Molecular emission reveals **resolved** inverse P-Cygni profile (the only one known so far), indicative of strong infall.

Pineda et al. (2012)
Zapata et al. (2013)
Hernandez et al. (2017)

The central part of the HL Tau disk

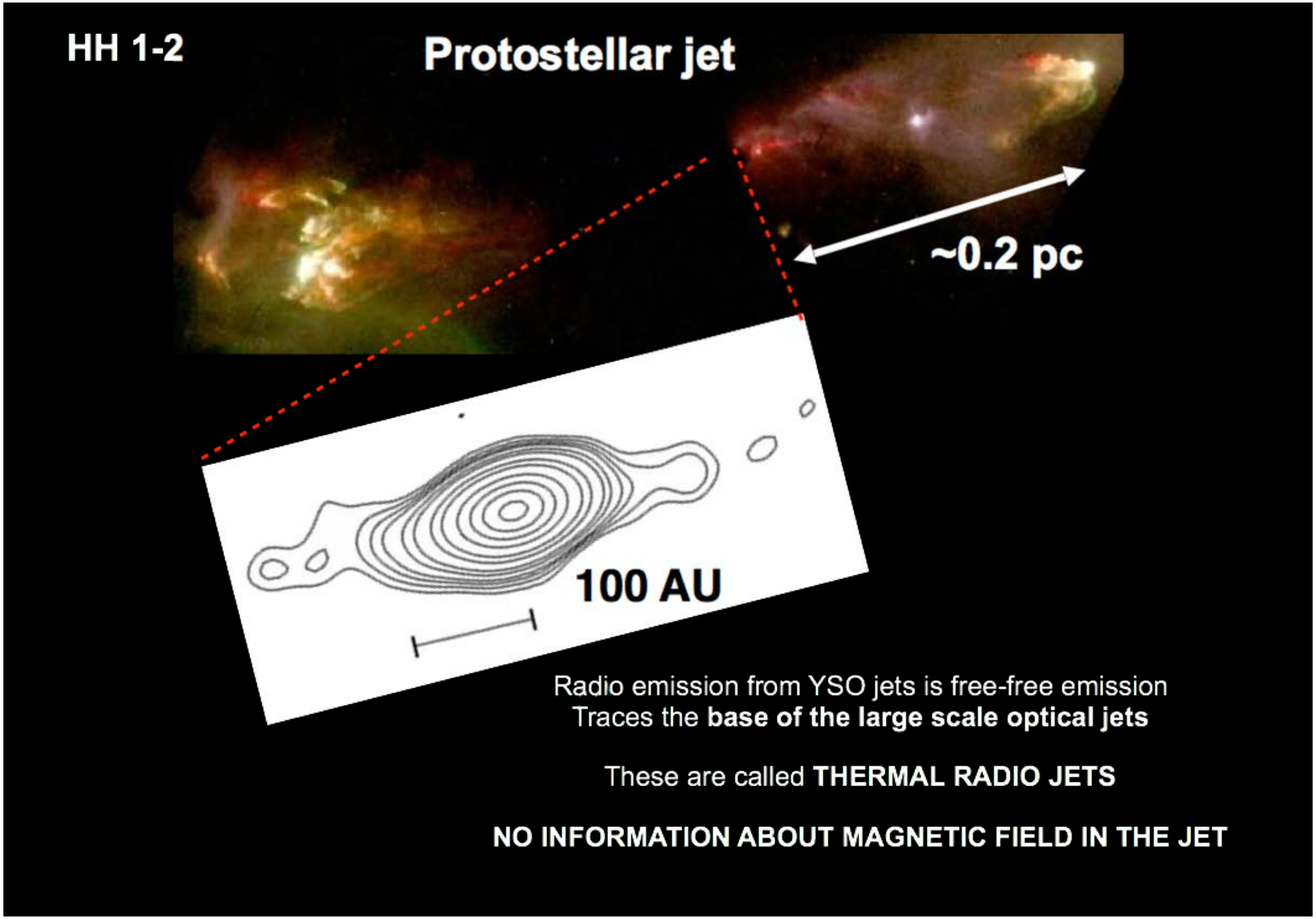


Thermal dust radio emission from protoplanetary disks can help characterize the region of terrestrial planet formation

Central ~10 AU is region of terrestrial planet formation. Optically thick at mm wavelengths, but transparent at cm wavelengths

Carrasco-González et al. (2014)

Thermal jets (shock ionized gas at the base of protostellar jets)

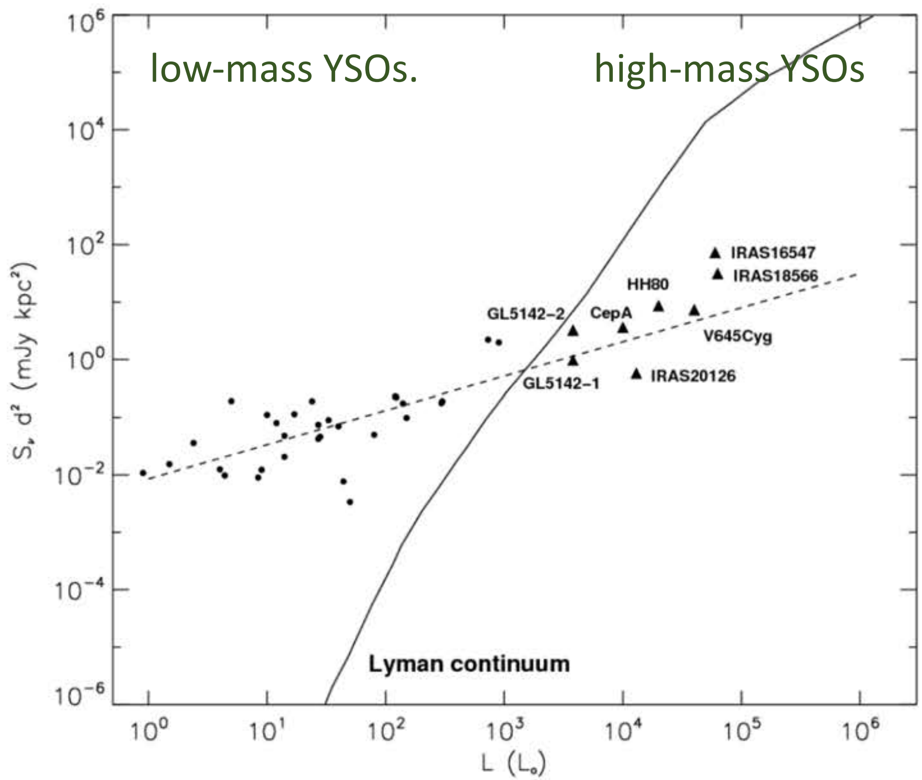


See review paper by Anglada et al. (2010)

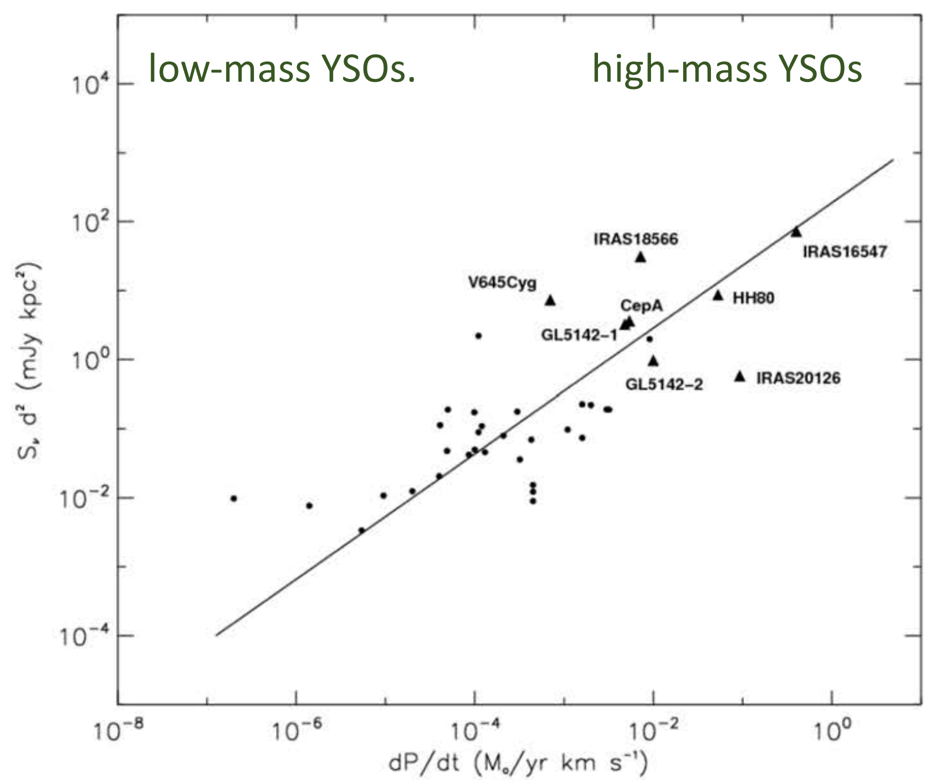
Thermal jets (shock ionized gas at the base of protostellar jets)

Thermal jet radio luminosity

vs. bolometric luminosity



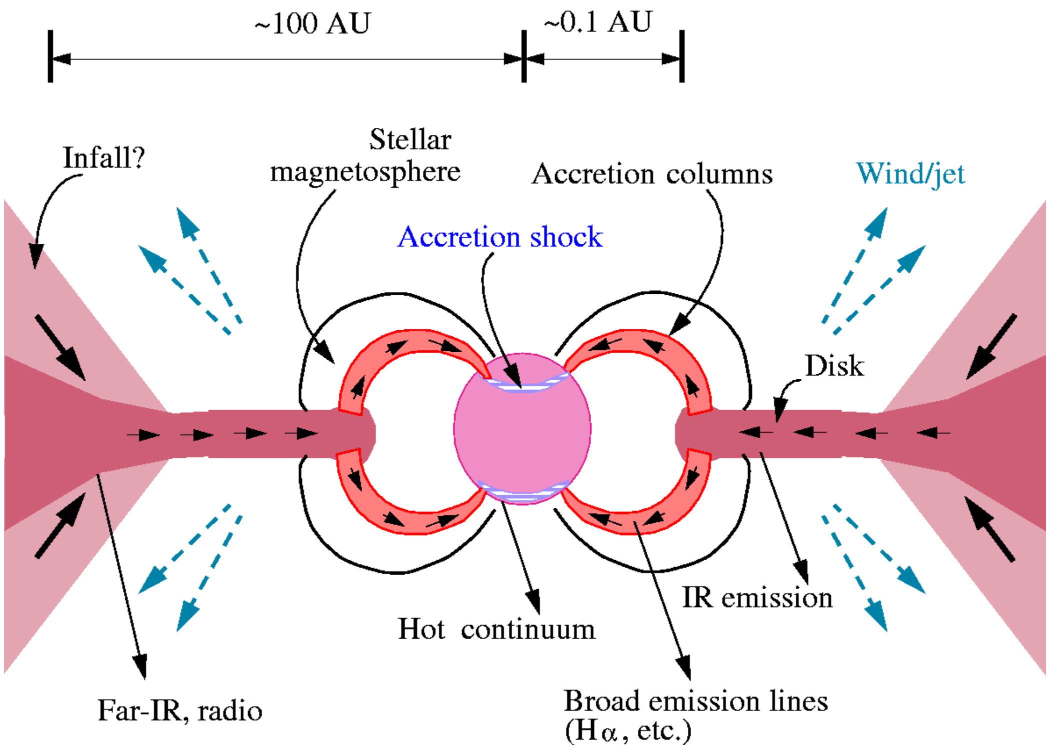
vs. mechanical luminosity

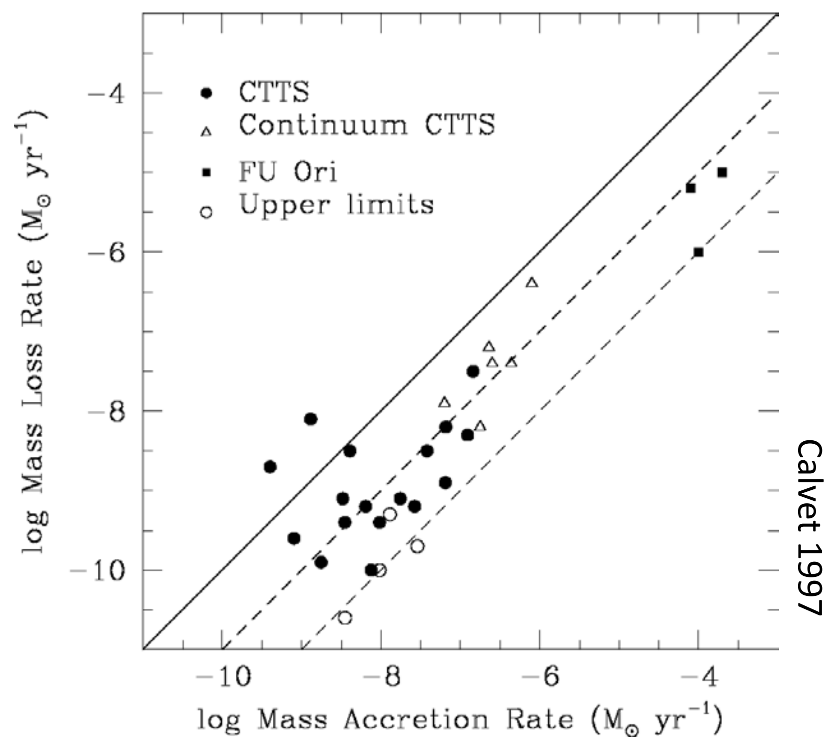


See review paper by Anglada et al. (2010)

Thermal jets as tracers of variable accretion/ejection processes?

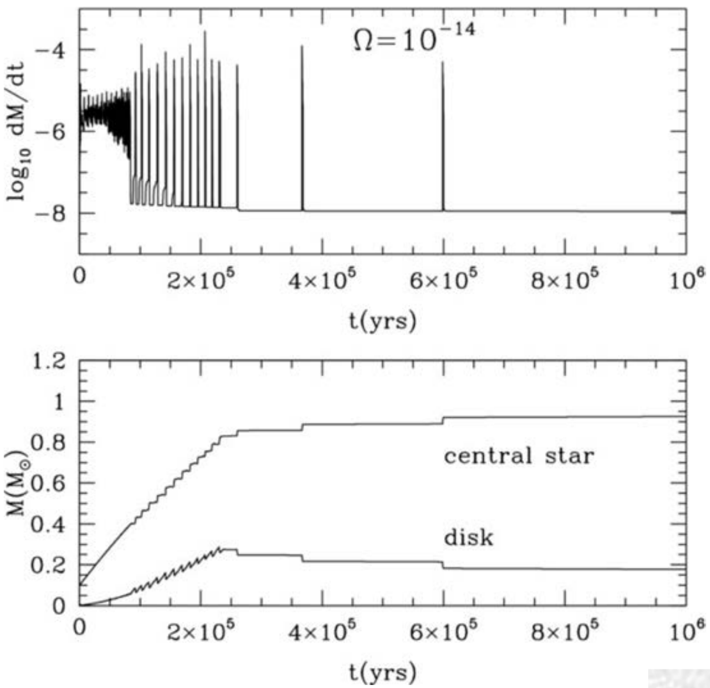
- The most popular mechanisms (magneto-centrifugal) have the winds launched from the inner 0.1 AU of the disks (Blandford & Payne 1982, Pudritz & Norman 1983).
- Theoretical models predict that about $M_{ejected} = 0.3\ M_{accreted}$ (Shu et al. 1988, 1994).

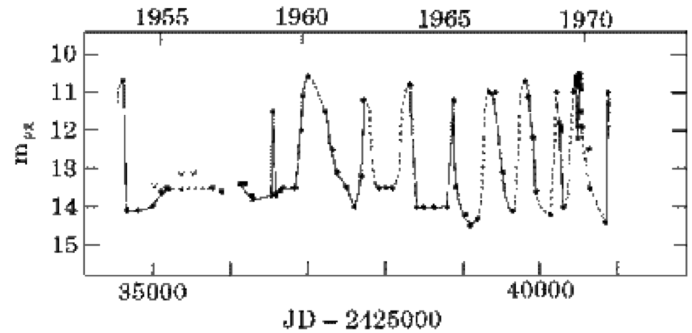




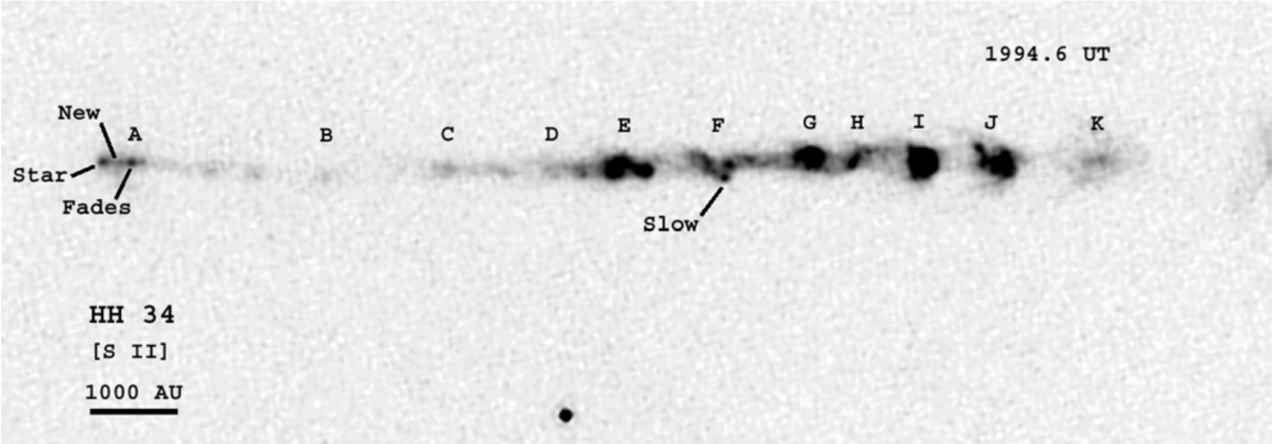
Thermal jets as tracers of variable accretion/ejection processes?

Zhu, Hartmann & Gammie (2010)

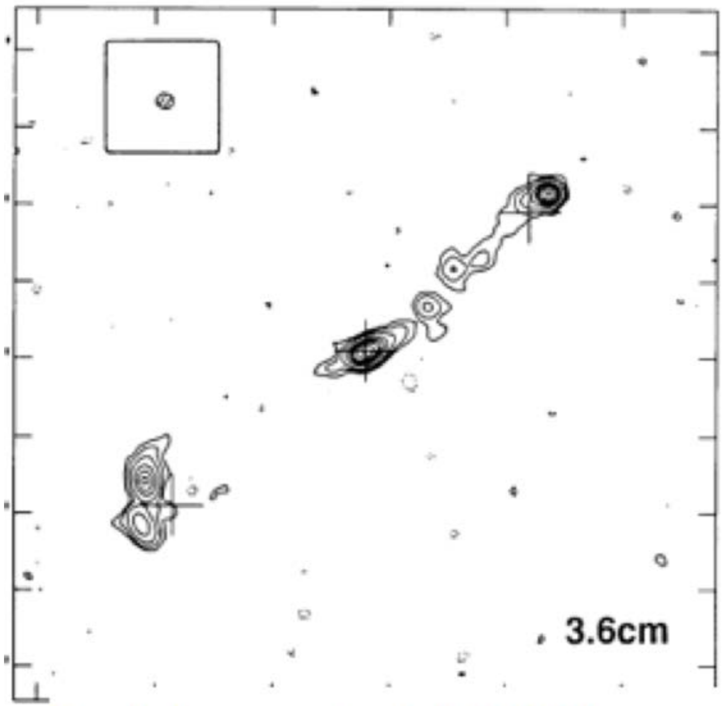




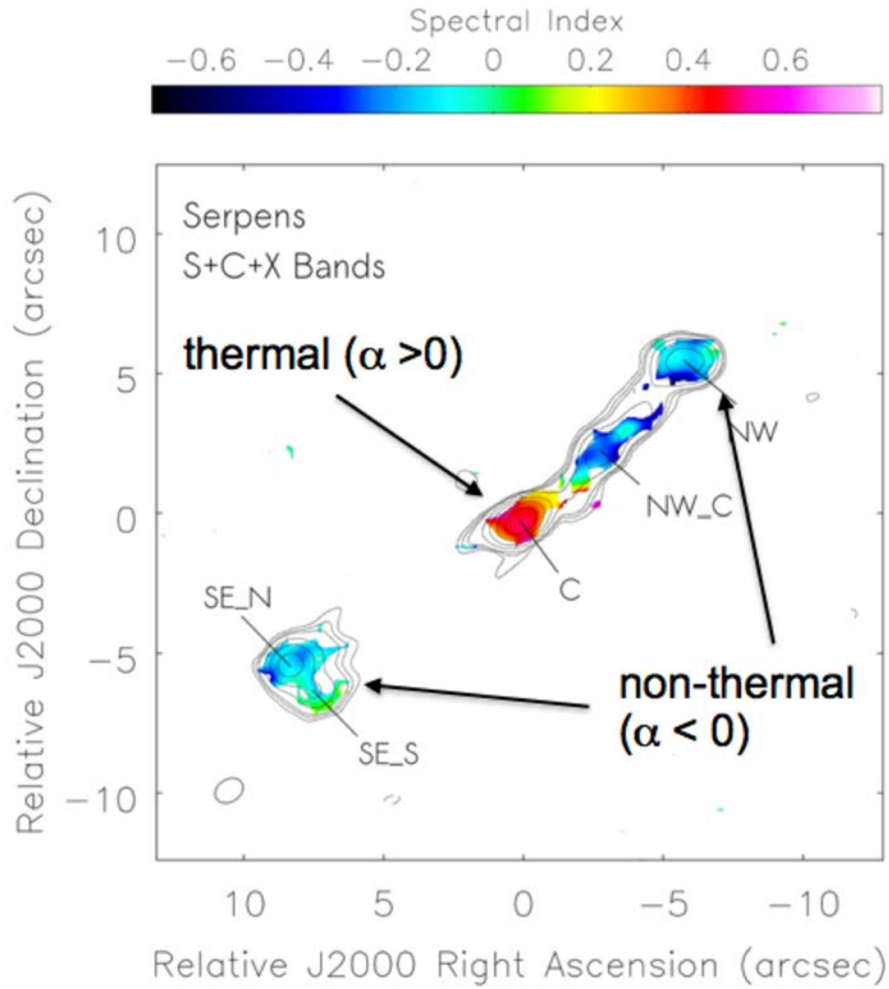
Herbig (1977)



Non-thermal jets



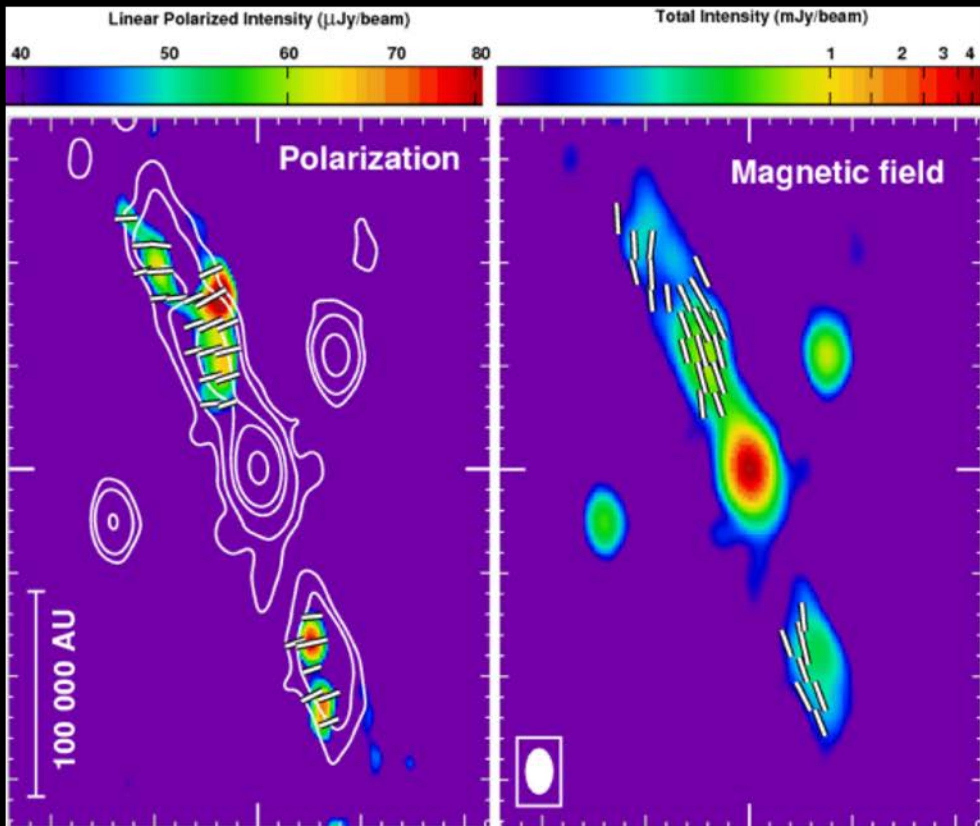
Rodríguez et al. (1989)



Rodríguez-Kamenetski et al. (2016)

Non-thermal jets

First (and still unique) detection of linearly polarized emission at cm wavelengths in a protostellar jet



Confirmation of synchrotron emission in protostellar jets

1. Particle acceleration mechanism
2. Possibility of studying magnetic field

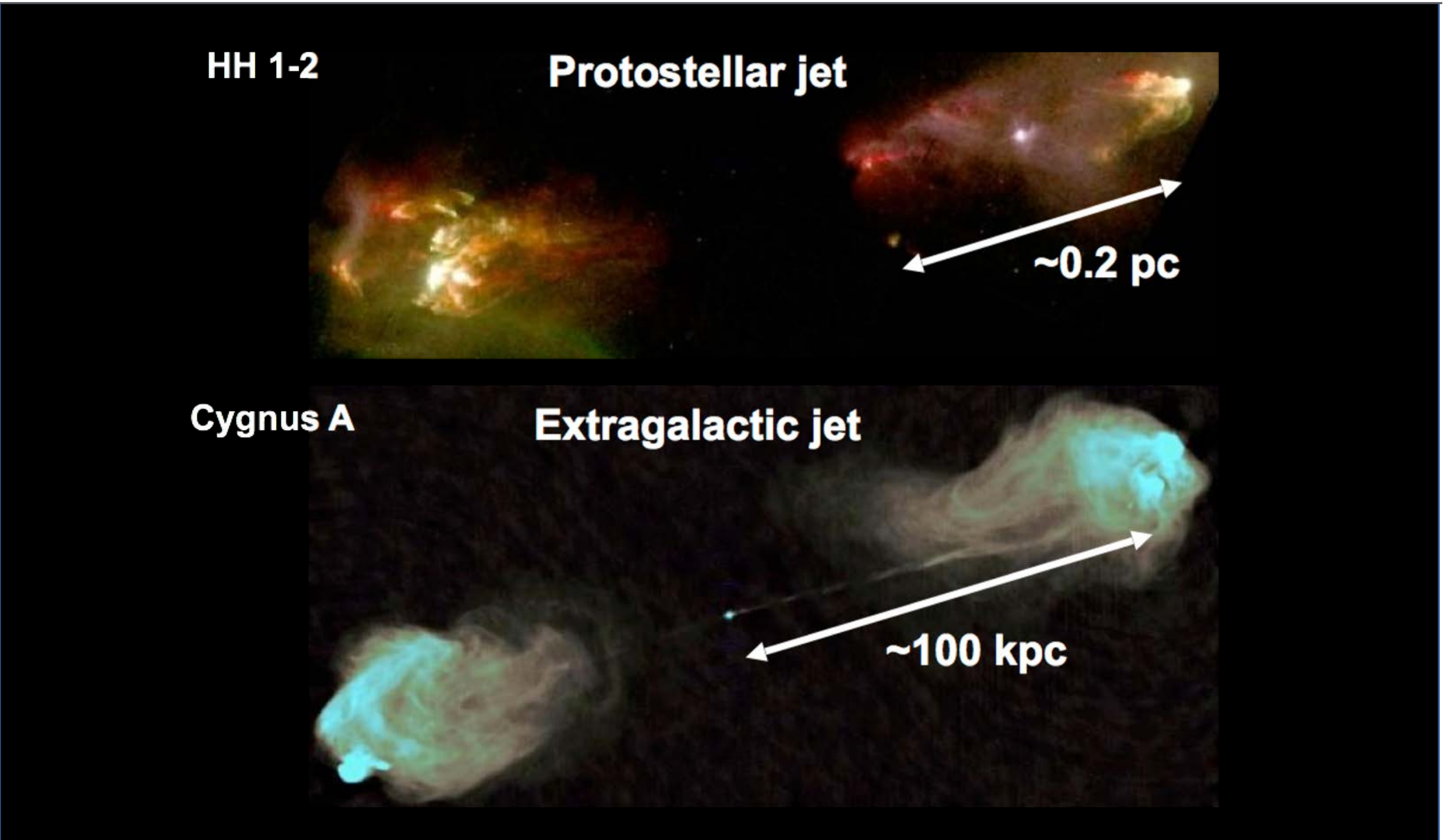
"Massive" protostar (~10 Msun)

"Fast" Jet -> 1000 km/s

Jet very well embedded in dense material

Linear polarization at 6 cm after 12 hours of VLA observation

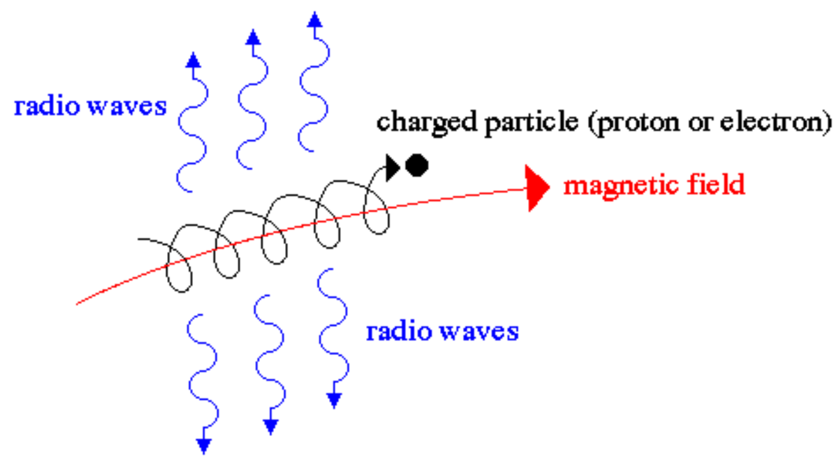
Non-thermal jets: extragalactic analogs?



Gyro-emission

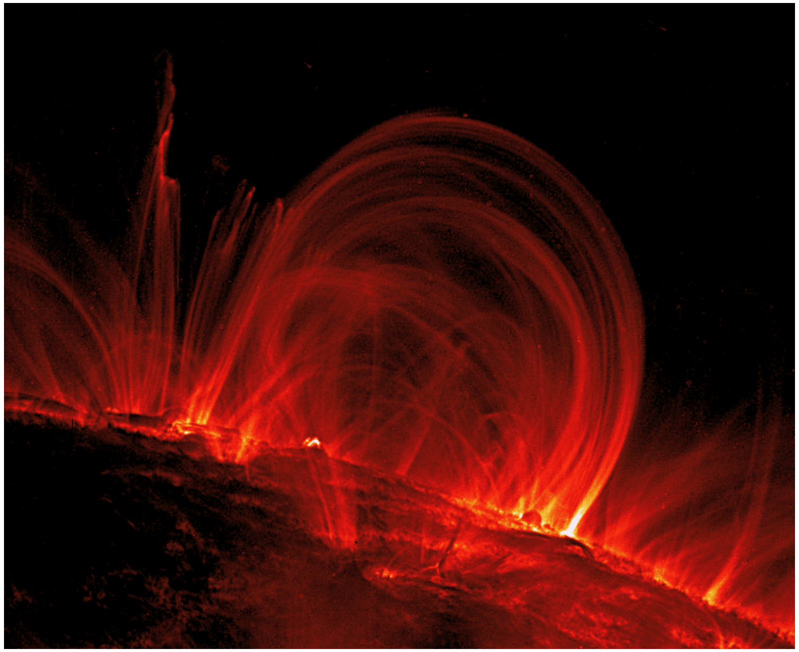
Miscellaneous terminology and facts:

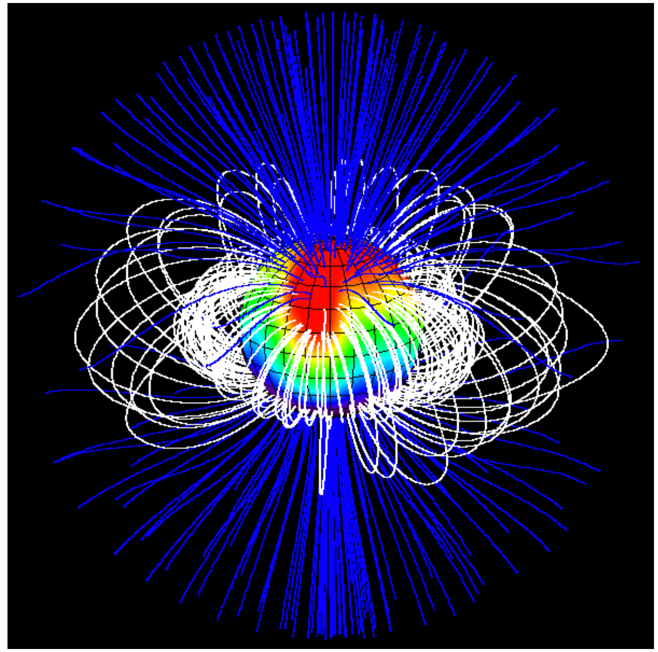
- If electrons are non-relativistic ($\gamma \sim 1$), the emission is called cyclotron.
    - ✓ Circular polarization (potentially up to 100%), too weak to be detectable in extrasolar sources except with amplification.
- If electrons are mildly relativistic (γ of a few) the emission is called gyro-synchrotron.
    - ✓ Moderate circular polarization, dominant mechanism in YSOs.
- If electrons are ultra relativistic ($\gamma >> 1$), the emission is called synchrotron.
    - ✓ Linear polarization.
- Usually, the velocity distribution of the electrons is **not** Maxwellian and those mechanisms are non-thermal. Acceleration of electrons is through Fermi mechanism in ISM, magnetic reconnection in stellar coronae. But see talk by Robert Mutel this afternoon.



Gyro-emission in YSOs

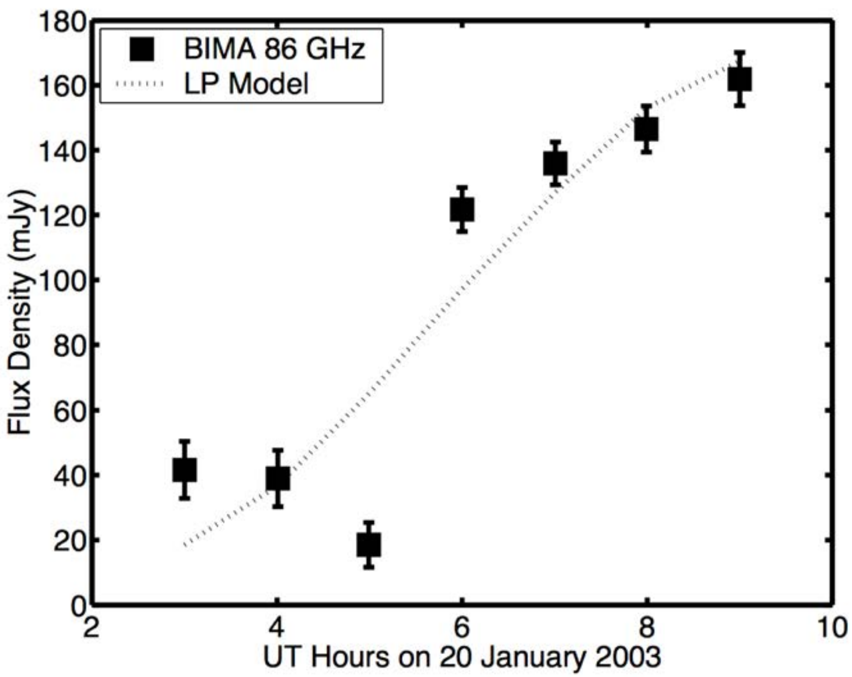
- Associated with active magnetospheres.



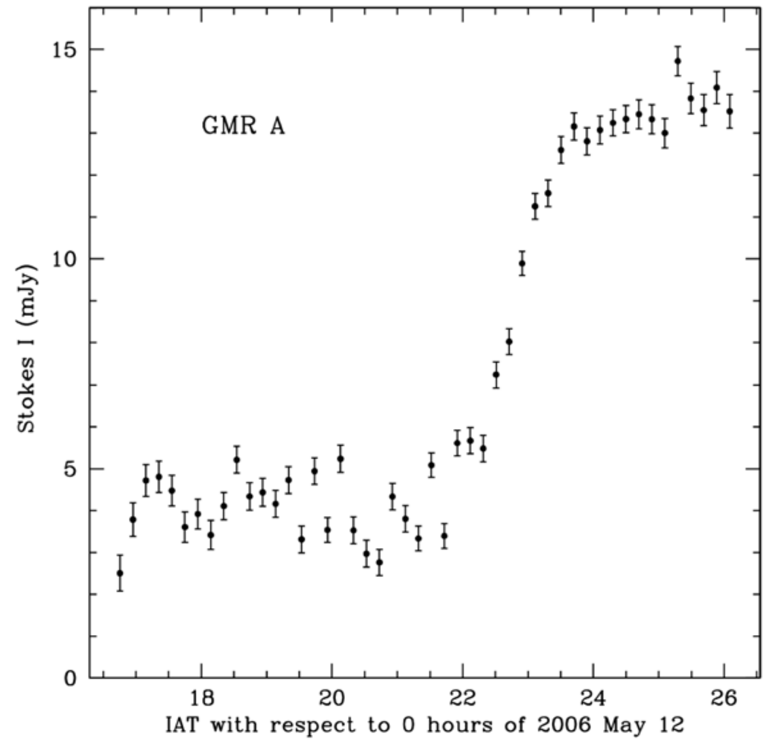


Gyro-emission in YSOs

- Associated with active magnetospheres.
- Almost always highly variable (flares).



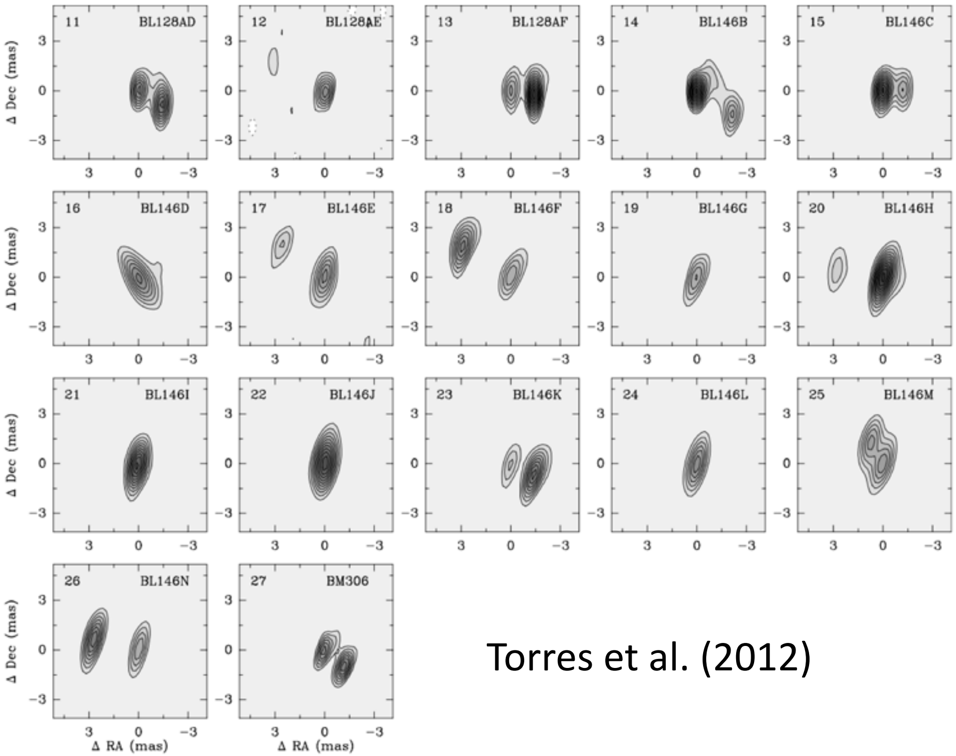
Bower et al. (2003)



Gómez et al. (2008)

Gyro-emission in YSOs

- Associated with active magnetospheres.
- Almost always highly variable (flares).
- Occasionally detectable circular polarization (but not always: requires organized B fields).
- Known cases are non-thermal; Tb in excess of about 10^7 K; detectable on very long baselines (VLBI).



Torres et al. (2012)

Gyro-emission in YSOs

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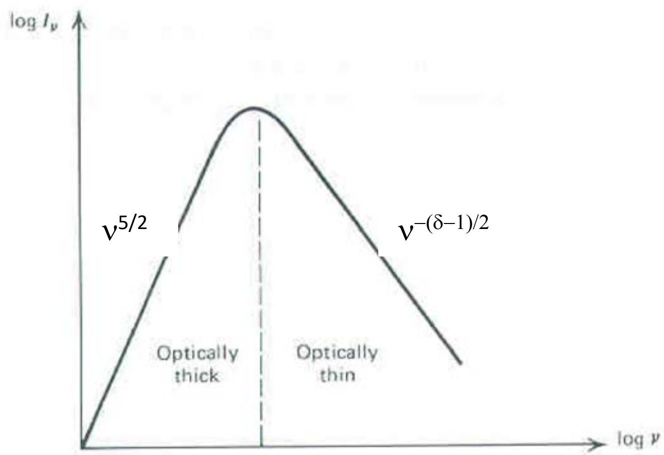
- Spectral index (for gyro-synchrotron) can be anywhere between something negative and +2.5 depending on emission opacity (potentially detectable at very low frequency; see talk with Rachael Ainsworth later today).

Slide From T. Bastian



Assuming a power-law energy distribution for the electrons:

$$N(E)dE = CE^{-\delta}dE$$

Gyro-emission in YSOs

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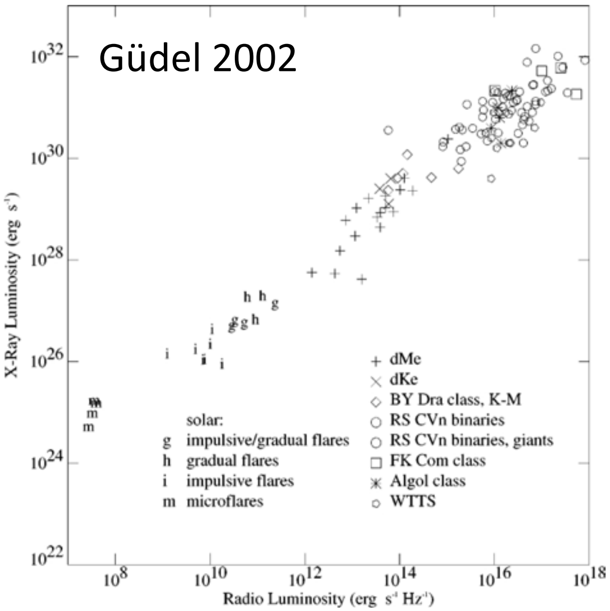
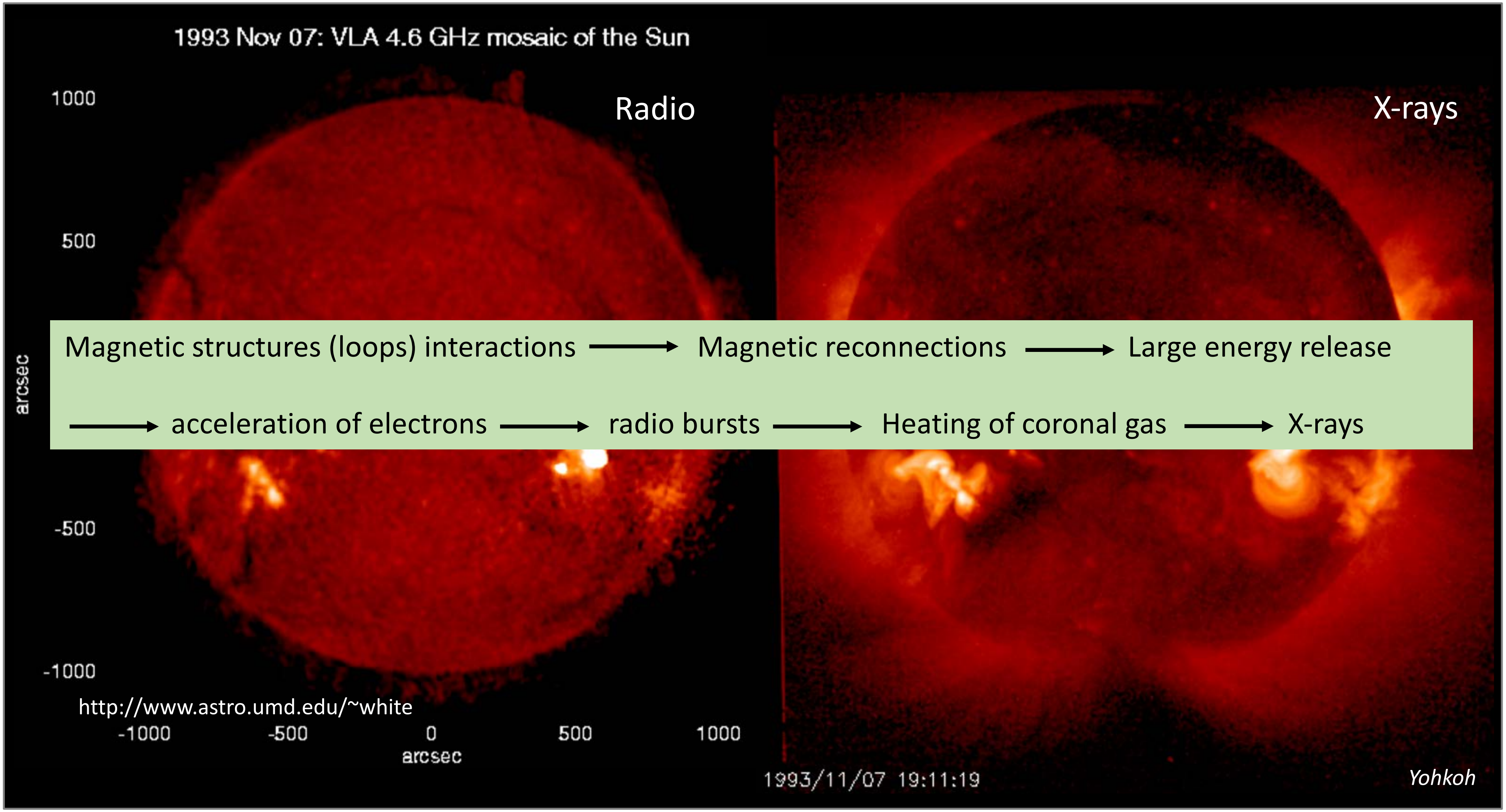
- Spectral index (for gyro-synchrotron) can be anywhere between something negative and +2.5 depending on emission opacity (potentially detectable at very low frequency; see talk with Rachael Ainsworth later today).
- Radio emission correlates with X-ray luminosity (Güdel-Benz relation)

Talk by Scott Wolk on simultaneous VLA-Chandra observations of Orion.



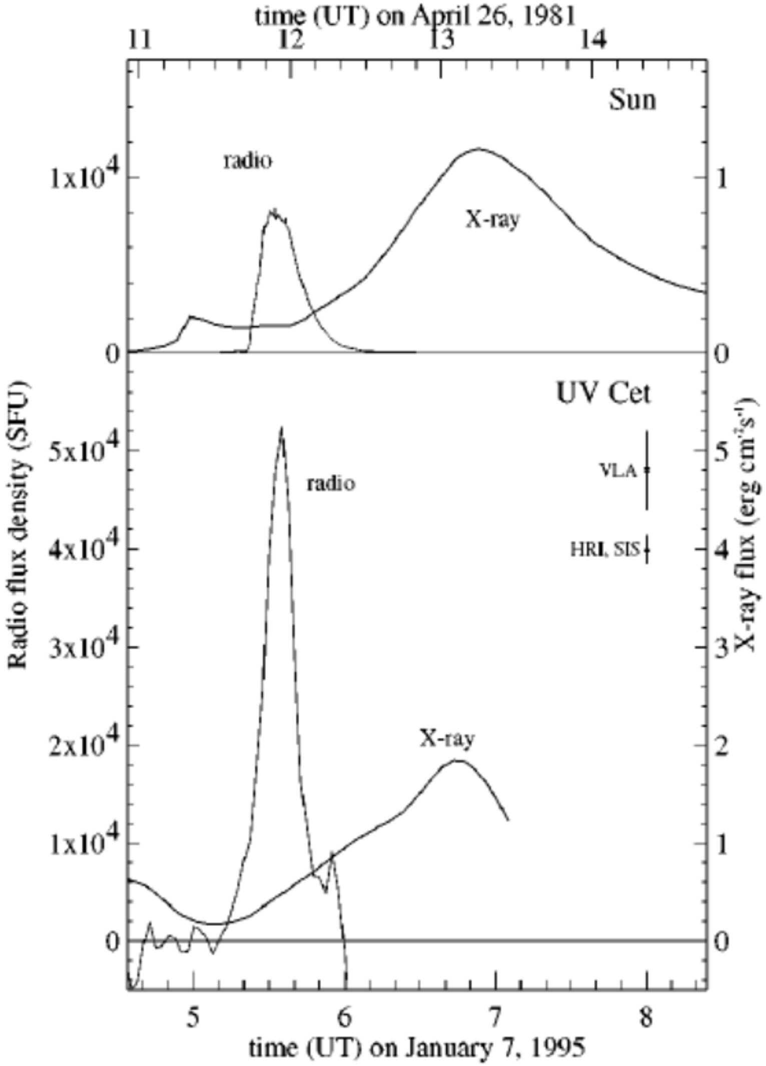
The Solar paradigm



Magnetic structures (loops) interactions → Magnetic reconnections → Large energy release → acceleration of electrons → radio bursts → Heating of coronal gas → X-rays

http://www.astro.umd.edu/~white

The Solar paradigm



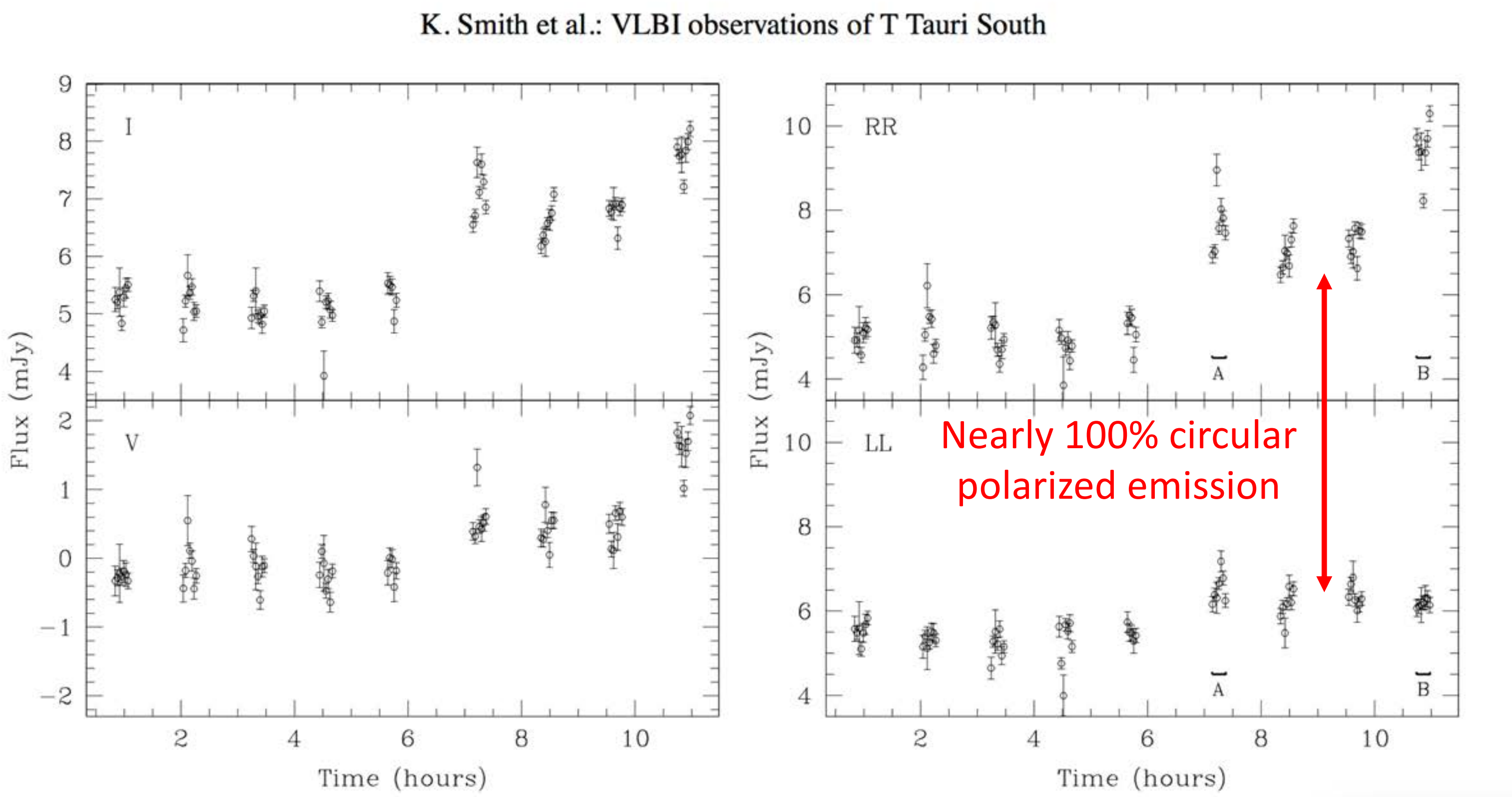
Different timescales for electron acceleration and Heating/cooling of magnetosphere leads to different Behavior for radio and X-rays (Neupert 1968)

The radio luminosity traces the fast electrons and thus the energy injected in a flare. The X-rays trace the accumulated energy.

Figure: Neupert effect seen in an M dwarf star, compared with a solar example in the upper panel (Güdel et al. 1996).

The variety of gyro-emission in YSOs

An electron maser cyclotron in T Tau Sb?



Smith et al. (2003)

Synchrotron emission in V773 Tau?

Synchrotron emission from the T Tauri binary system V773 Tauri A

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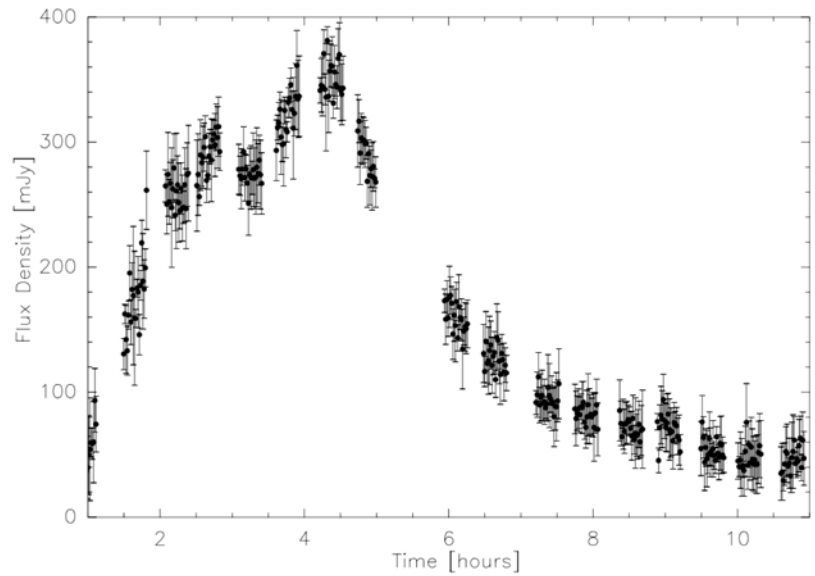
Received 30 May 2005 / Accepted 6 March 2006

ABSTRACT

The pre-main sequence binary system V773 Tau A shows remarkable flaring activity around periastron passage. Here, we present the observation of such a flare at a wavelength of 3 mm (90 GHz) performed with the Plateau de Bure Interferometer*. We examine different possible causes for the energy losses responsible for the e-folding time of 2.31 ± 0.19 h of that flare. We exclude synchrotron, collisional, and inverse Compton losses because they are not consistent with observational constraints, and we propose that the fading of the emission is due to the leakage of electrons themselves at each reflection between the two mirror points of the magnetic structure partially trapping them. The magnetic structure compatible with both our leakage model and previous observations is that of a helmet streamer that, as in the solar case, can occur at the top of the X-ray-emitting, stellar-sized coronal loops of one of the stars. The streamer may extend up to $\sim 20\ R_*$ and interact with the corona of the other star at periastron passage, causing recurring flares. The inferred magnetic field strength at the two mirror points of the helmet streamer is in the range 0.12–125 G, and the corresponding Lorentz factor, γ, of the partially trapped electrons is in the range $20 < \gamma < 632$. We therefore rule out that the emission could be of gyro-synchrotron nature: the derived high Lorentz factor proves that the nature of the emission at 90 GHz from this pre-main binary system is synchrotron radiation.

Key words. stars: coronae – stars: individual: V773 Tau A – stars: flare – stars: pre-main sequence – radio continuum: stars – stars: activity



The variety of gyro-emission in YSOs

Synchrotron emission in V773 Tau?

POLARIZED RADIO EMISSION FROM THE MULTIPLE T TAURI SYSTEM HD 283447

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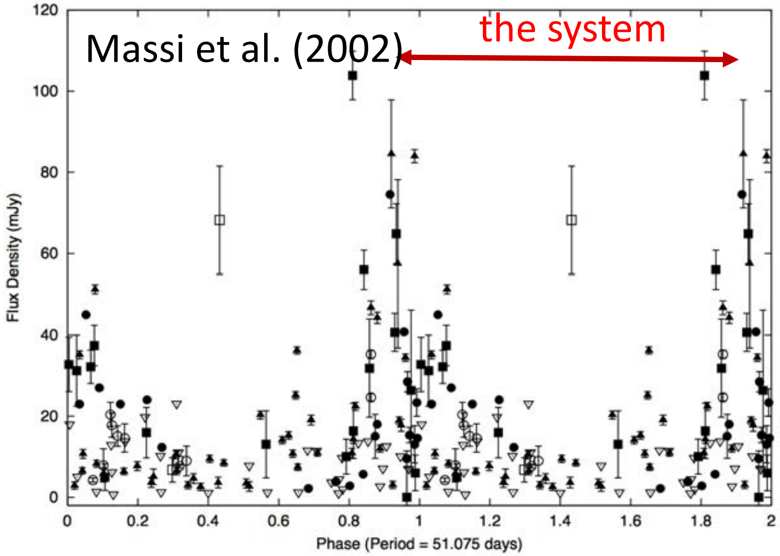
Received 1995 September 8; revised 1995 October 23

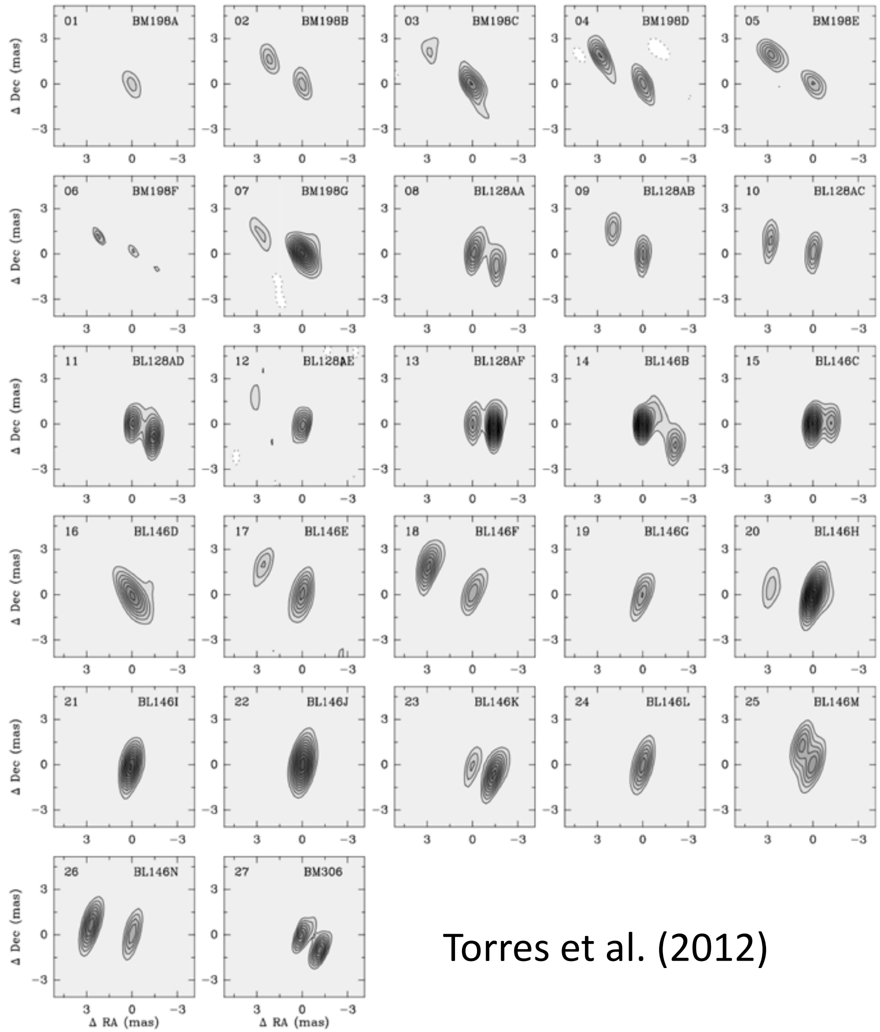
ABSTRACT

The pre-main-sequence multiple system HD 283447, one of the brightest T Tauri objects in the Taurus–Auriga complex, is a luminous nonthermal stellar radio source. It is a very young system with properties intermediate between classical and weak-lined T Tauri stars. We report a series of simultaneous VLBI/VLA observations which confirm earlier evidence for complex radio-emitting structures which are resolved only with VLBI. These structures at times achieve $\sim\frac{1}{3}$ AU in extent, and, in one epoch, a double radio source corresponds well with the projected orbital separation for the inner binary. Both K stars in the close binary appear to be active radio stars. Circular and *linear* polarization are seen in the continuum radio emission from HD 283447. The presence of linearly polarized nonthermal radiation provides evidence for a higher-energy electron population than previously deduced from emission from any other nonthermal stellar radio source.

The relation between gyro-emission and multiplicity in YSOs



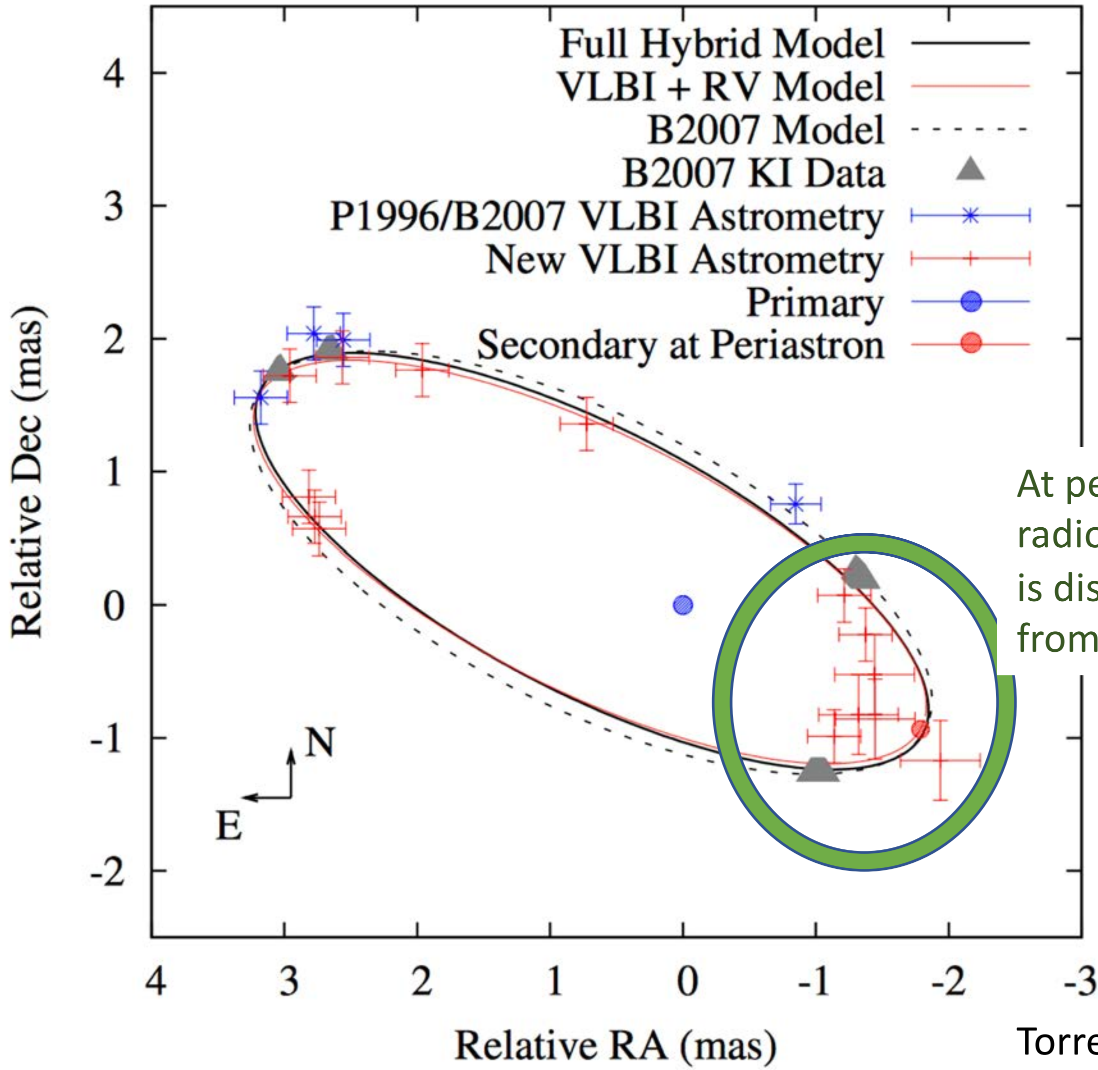
See talk by Amy Mioduszewski for more VLBI



Torres et al. (2012)

The relation between gyro-emission and multiplicity in YSOs

Orbital path measured from NIR and VLBI astrometry



At periastron, radio emission is displaced from stars

Torres et al. (2012)

How common is gyro-emission in YSOs?

Roughly half (and nearly all WTTS) of the VLA-detected YSOs in Ophiuchus are also detected on VLBI baselines

Table 2. Detected YSOs

GBS-VLA name[1] (1)	Other identifier (2)	Minimum flux at 5 GHz (mJy) (3)	Maximum flux at 5 GHz (mJy) (4)	Minimum flux at 8 GHz (mJy) (5)	Maximum flux at 8 GHz (mJy) (6)	log [T_b (K)] (7)	SED Class (8)	Num. of detc./obs. (9)	A_V (10)
J162556.09-243015.3	WLY2-11a	0.13±0.05	0.27±0.06	–		>7.0	Class III	4/5	13
J162556.09-243015.3	WLY2-11b	0.86±0.05		0.60±0.09		7.9		2/5	
J162557.51-243032.1	YLW24	0.21±0.05	1.35±0.06	0.25±0.06		8.0	Class III	4/5	13
J162603.01-242336.4	DOAR21	1.98±0.11	14.97±0.14	4.13±0.07	5.66±0.07	9.2	Class III	7/7	12
J162616.84-242223.5	LFAMP1	0.15±0.06	0.47±0.04	–		6.8	Class II	2/6	20
J162622.38-242253.3	LFAM2	0.30±0.05	0.38±0.07	<0.09		>6.7	Class II	3/7	20
J162625.62-242429.2	LFAM4	0.66±0.12		<0.12		>6.9	Class I	1/14	17
J162629.67-241905.8	LFAM8	0.37±0.06	1.18±0.13	0.26±0.07	0.30±0.05	7.3	Class III	7/9	19
J162634.17-242328.4	S1[2]	5.56±0.15	7.58±0.07	3.27±0.14		9.2	Class III	8/8	18
J162642.44-242626.1	LFAM15a	0.28±0.05	0.93±0.06	0.25±0.06	1.50±0.06	7.8	Class III	10/10	18
J162642.44-242626.1									
J162643.76-241633.4									14
J162643.76-241633.4									
J162649.23-242003.3									18
J162651.69-241441.5									12
J162705.16-242007.8									19
J162718.17-242852.9									26
J162718.17-242852.9									
J162718.17-242852.9									
J162719.50-244140.3									22
J162721.81-244335.9	ROXN39a	0.22±0.07	1.44±0.07	0.24±0.06	0.44±0.08	7.9	Class III	7/15	20
J162721.81-244335.9	ROXN39b	0.22±0.05	0.81±0.06	0.57±0.09		7.6		5/15	
J162724.19-242929.8	GY257	0.97±0.06		<0.09		>7.0	Class III	1/8	13
J162726.90-244050.8	YLW15	0.18±0.04	0.25±0.08	0.23±0.08	0.33±0.06	7.1	Class I	5/11	25
J162730.82-244727.2	DROXO71	0.30±0.05	0.91±0.05	0.60±0.07	1.15±0.09	8.0	Class III	8/9	8
J162804.65-243456.6	ROXN78	0.38±0.04		<0.12		>6.6	Class II	1/4	20
J163035.63-243418.9	SFAM87a	0.48±0.05	2.64±0.09	–		8.1	CTTS	4/4	3
J163035.63-243418.9	SFAM87b	0.28±0.06	1.35±0.06	–		7.8		3/4	
J163115.01-243243.9	ROX42B	0.21±0.06	0.38±0.08	<0.12		7.0	WTTS	2/5	3
J163120.18-243001.0	ROX43B	0.20±0.05	1.20±0.08	<0.12		>7.1	WTTS	3/5	3
J163152.10-245615.7	LDN1689IRS5	0.23±0.05	3.17±0.08	0.64±0.07		8.3	FS	4/4	18
J163200.97-245643.3	WLY2-67	0.18±0.05	0.41±0.07	–		>6.6	Class I	3/3	14
J163211.79-244021.8	DOAR51a	0.40±0.07	3.14±0.06	0.69±0.08		8.5	WTTS/Class II	7/7	8
J163211.79-244021.8	DOAR51b	0.24±0.06	0.68±0.07	0.47±0.08		7.6		7/7	

By the way, many are tight binary systems…

Ortiz-Leon et al. 2017

That's very useful for astrometry…

THE GOULD'S BELT DISTANCES SURVEY (GOBELINS) I.
TRIGONOMETRIC PARALLAX DISTANCES AND DEPTH OF THE OPHIUCHUS COMPLEX

GISELA N. ORTIZ-LEÓN[1], LAURENT LOINARD[1,2], MARINA A. KOUNKEL[3], SERGIO A. DZIB[2], AMY J. MIODUSZEWSKI[4], LUIS F. RODRÍGUEZ[1,5], ROSA M. TORRES[6], ROSA A. GONZÁLEZ-LÓPEZLIRA[1,13,14], GERARDO PECH[1,7], JUANA L. RIVERA[1], LEE HARTMANN[3], ANDREW F. BODEN[8], NEAL J. EVANS II[9], CESAR BRICEÑO[10], JOHN J. TOBIN[11], PHILLIP A. B. GALLI[12,15], AND DONALD GUDEHUS[16]

ABSTRACT

We present the first results of the *Gould's Belt Distances Survey (GOBELINS)*, a project aimed at measuring the proper motion and trigonometric parallax of a large sample of young stars in nearby regions using multi-epoch Very Long Baseline Array (VLBA) radio observations. Enough VLBA detections have now been obtained for 16 stellar systems in Ophiuchus to derive their parallax and proper motion. This leads to distance determinations for individual stars with an accuracy of 0.3 to a few percent. In addition, the orbits of 6 multiple systems were modelled by combining absolute positions with VLBA (and in some cases, near infrared) angular separations. Twelve stellar systems are located in the dark cloud Lynds 1688; the individual distances for this sample are highly consistent with one another, and yield a mean parallax for Lynds 1688 of $\varpi = 7.28 \pm 0.06$ mas, corresponding to a distance $d = 137.3 \pm 1.2$ pc. This represents an accuracy better than 1%. Three systems for which astrometric elements could be measured are located in the eastern streamer (Lynds 1689) and yield an estimate of $\varpi = 6.79 \pm 0.16$ mas, corresponding to a distance $d = 147.3 \pm 3.4$ pc. This suggests that the eastern streamer is located about 10 pc farther than the core, but this conclusion needs to be confirmed by observations (currently being collected) of additional sources in the eastern streamer. From the measured proper motions, we estimate the one-dimensional velocity dispersion in Lynds 1688 to be 2.8±1.8 and 3.0±2.0 km s^{-1}, in R.A. and DEC., respectively; these are larger than, but still consistent within 1σ, with those found in other studies.

Keywords: astrometry - radiation mechanisms: non-thermal - radio continuum: stars - techniques: interferometric

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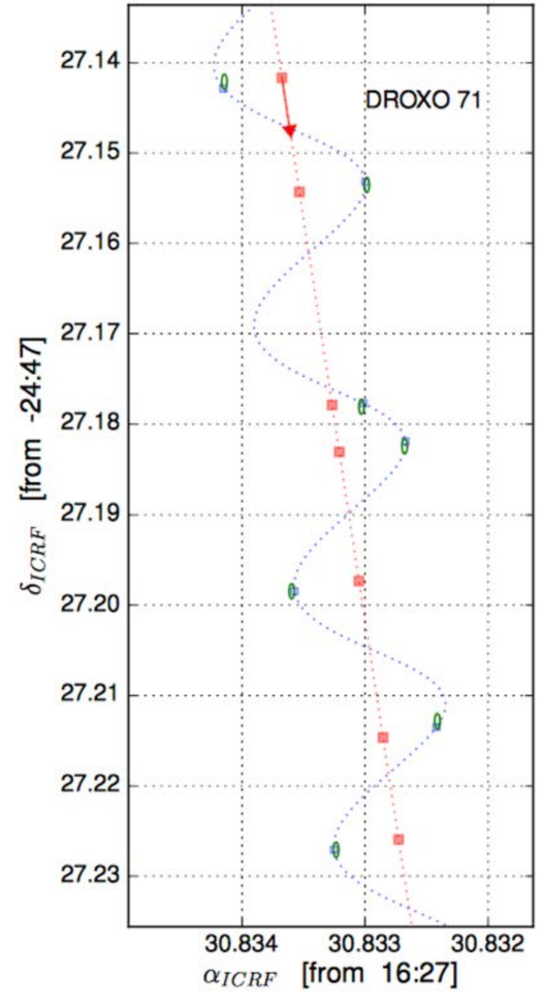
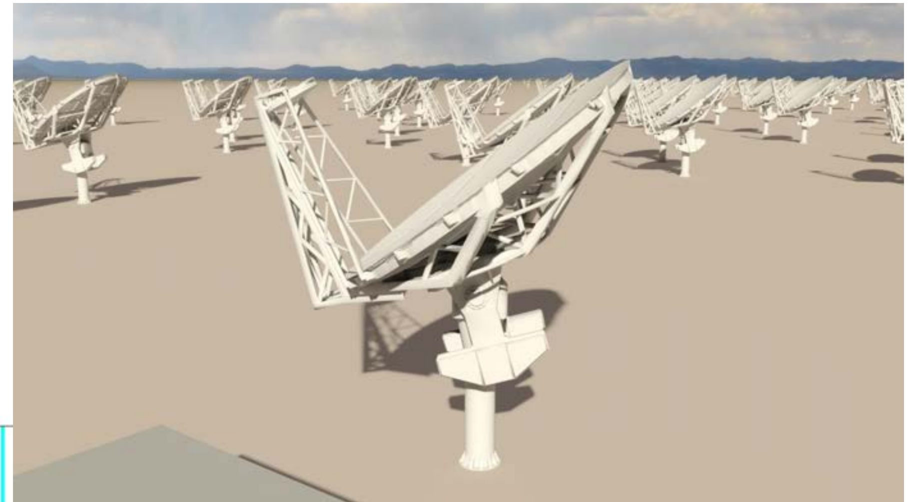


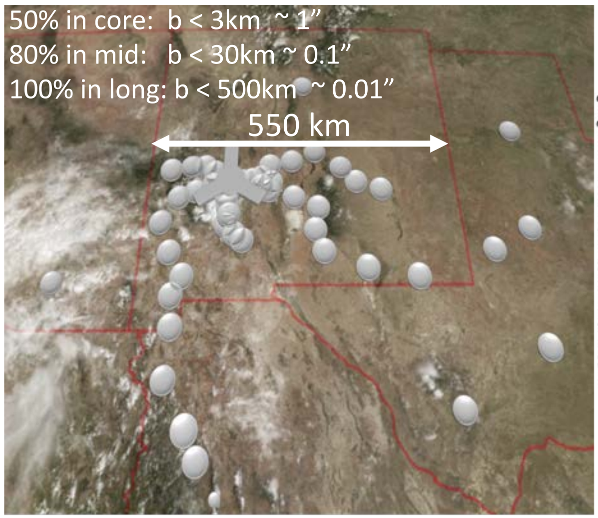
Conclusions…

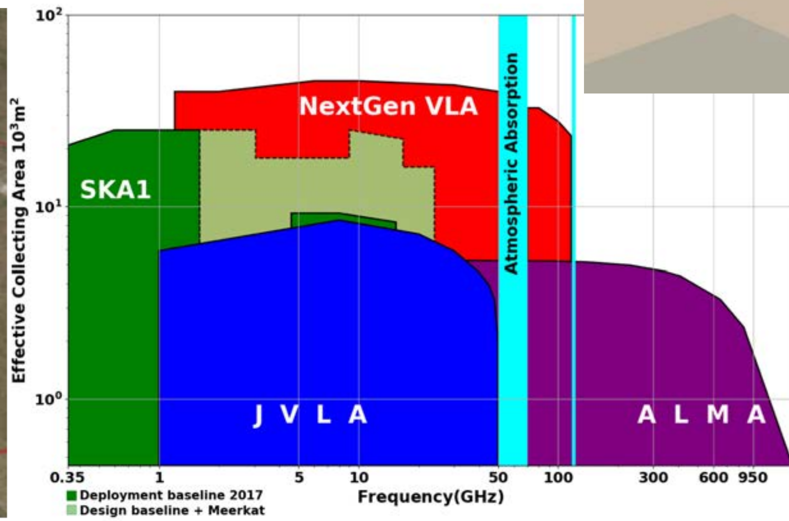
- Radio emission is common in young stars and provide constraints on many important phenomena.
  - ✓ Thermal dust emission from envelopes/disks
  - ✓ Thermal bremsstrahlung from partially ionized jets
  - ✓ Synchrotron from jet (singular, so far..)
  - ✓ Gyro-emission from magnetically active YSOs

A next-generation Very Large Array (ngVLA)

- Scientific Frontier: ***Thermal imaging at milli-arcsec resolution***
- Sensitivity/Resolution Goal:
  - ***10x effective collecting area & resolution of JVLA/ALMA***
- Frequency range: ***1.2 –116 GHz***
- Located in Southwest U.S. (NM+TX) & MX, centered on VLA
- Baseline design under active development
- Low technical risk (reasonable step beyond state of the art)







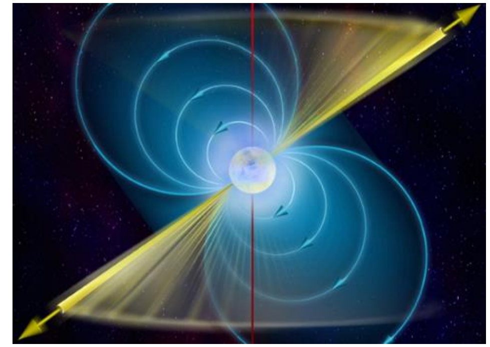
Complementary suite from meter to submm arrays for the mid-21st century

- **< 0.3cm:** ALMA 2030
- **0.3 to 3cm: ngVLA**
- **> 3cm:** SKA

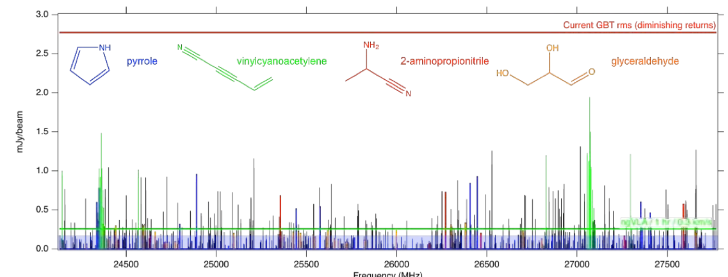
https://science.nrao.edu/futures/ngvla

ngVLA Key Science Mission

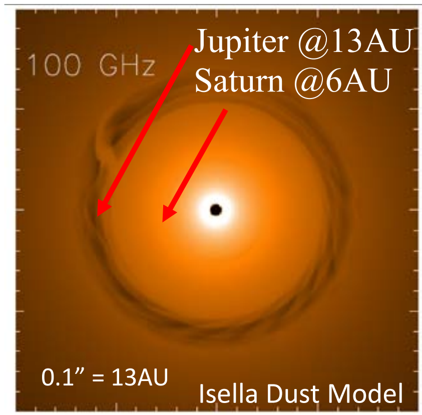
(ngVLA memo #19)

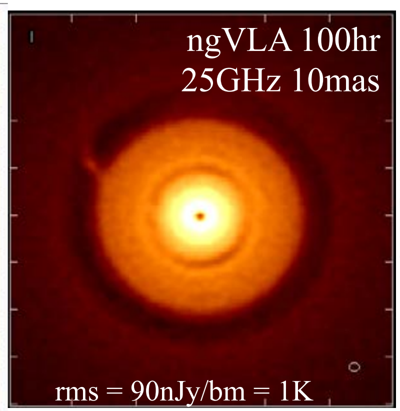


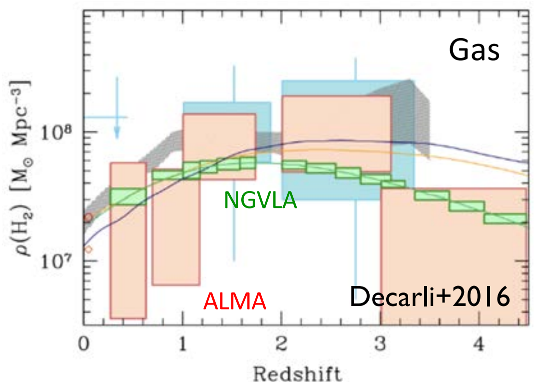
- ***Unveiling the Formation of Solar System Analogues***
- ***Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry***
- ***Charting the Assembly, Structure, and Evolution of Galaxies Over Cosmic Time***
- ***Using Pulsars in the Galactic Center as Fundamental Tests of Gravity***
- ***Understanding the Formation and Evolution of Stellar and Supermassive BH’s in the Era of Multi-Messenger Astronomy***

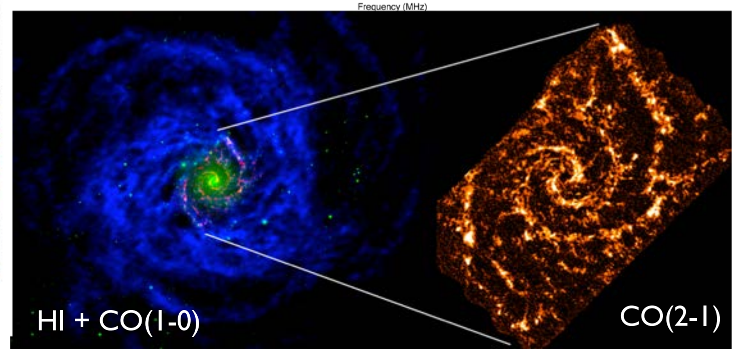


Highly synergistic with next-generation ground-based OIR and NASA missions.







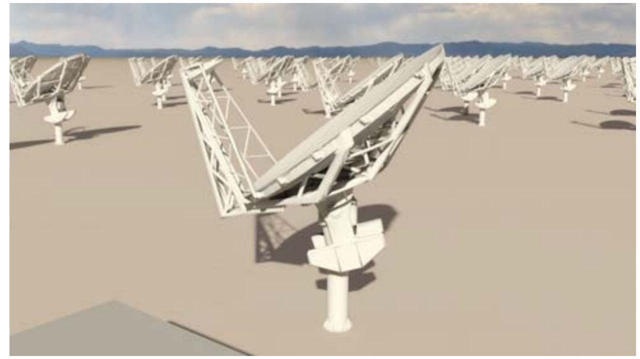


Current Reference Design Specifications

(ngVLA Memo #17)

- 214 18m offset Gregorian (feed-low) Antennas
  - Supported by internal cost-performance analysis
- Fixed antenna locations across NM, TX, MX
  - ~1000 km baselines being explored
- 1.2 – 50.5 GHz; 70 – 116 GHz
  - Single-pixel feeds
  - 6 feeds / 2 dewar package
- Short-spacing/total power array under consideration

- Continuum Sensitivity: ~0.1uJy/bm @ 1cm, 10mas, 10hr => T_B ~ 1.75K
- Line sensitivity: ~21.5uJy/bm @ 1cm, 10 km/s, 1”, 10hr => T_B ~ 35mK



Receiver Configuration

Band #	Dewar	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHz
1	A	1.2	2.55	3.9	3.25	2.7
2	B	3.9	8.25	12.6	3.23	8.7
3	B	12.6	16.8	21.0	1.67	8.4
4	B	21.0	28.0	35.0	1.67	14.0
5	B	30.5	40.5	50.5	1.66	20.0
6	B	70.0	93.0	116	1.66	46.0