VLBI PROPOSAL COVERSHEET

rcvd:

DEADLINES: 1st of Feb., June., Oct.

SEND TO: Director NRAO, Edgemont Rd. Charlottesville, VA 22903-2475, USA

(1) Date Prepared: February 3, 1997

(2) Proposal Title: Zooming in on Pre-Main-Sequence-Star-Forming Regions

(3) AUTHORS	INSTITUTION/LOCATION	For Grad Students Only Observations For Ph.D. Thesis?	 Anticipated Ph.D. Year
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(4) Related previous or current VLBI proposal(s):

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(6) Scientific Category (indicate all that apply):

○ astrometry & geodesy, ○ solar, ○ propagation, ○ planetary, ☒ stellar, ○ pulsar, ☒ ISM, ○ masers, ○ normal galaxies, ○ active galaxies, ○ cosmology

(7) Wavelength(s) requested (those not available on the global network are indicated with a small circle):

○ 90cm, ○ 50cm, ∘ 21cm, ○ 18cm, ○ 13cm, ○ 6cm, ☒ 3.6cm, ○ 3.6/13cm, ∘ 2cm, ○ 1.3cm, ○ 7mm

○ Global Network standard bands ○ Special frequencies ____________

(8) Recording format: ☒ VLBA ☒ MkIV ○ MkIII (Mode ____)

Aggregate bit rate 256 (8 BB channels at 16 MSamples/sec of ○ 1 bit, ☒ 2 bit samples)

(9) ○ Multi-epoch observation: ______ epochs of _______ hours each, separated by _________

(10) Network	Requested antennas	Total time requested
EVN		
VLBA	FD, LA, PT, KP, OV	18 h
US	Y27	18 h
DSN	Goldstone-70m	18 h
Unaffiliated		

(11) ABSTRACT (Do not write outside this space. Please type.)

Recent calculations suggest that it may be possible to directly observe shocked gas in the accretion disk and/or outflow associated with a forming star. We propose to attempt detection of this gas using VLBI techniques. If we succeed, our observations will represent the *first glimpse of structures within a few A.U. of a forming star.*

In order to make this experiment feasible, we have selected sources that have all been previously detected (but largely unresolved) at the VLA. The participation of the phased VLA and Goldstone-70m are critical to achieving adequate sensitivity.

Scheduler use only
(12/96)

(12) Observation type: ☒ Interferometry, ○ Spectroscopy, ○ Pulsar, ☒ Phase referencing, ○ Single dish

(13) Polarization: ○ IEEE RCP ○ IEEE LCP ☒ Dual Circular
Global network standard for single polarization is LCP for all λs except 13cm (RCP) and 3.6cm (RCP).

(14) Tape usage (Show <recording time>/<total time>): 5/6 (3 tapes)

(15) Assistance required:
Observation Setup: ☒ Consultation, ○ Extensive help, ○ Control file preparation
Correlation: ○ Consultation, ○ Extensive help, ○ Control file preparation
Postprocessing: ☒ Consultation, ○ Extensive help, ○ Control file preparation

(16) Processor: Socorro
Special processing: ○ XPol, ○ Pulsar gate, ☒ Multiple Fields: 2 for HL Tau/XZ Tau
Averaging time: ______ Spectral channels per baseband channel: 16
○ Other special processing: ______

(17) Postprocessing Location: CfA

(18) Source list: ○ J2000 ☒ B1950
If more than 4 sources, please attach list. If more than 30, give only selection criteria and GST range(s)

	Source 1	Source 2	Source 3	Source 4
Name(s)	HL Tau	XZ Tau	L1551-IRS5	NGC 1333
RA (hh mm)	04 29	04 29	04 29	03 25
Dec (dd.d)	18.1	18.1	18.1	31.2
GST range (Europe)				
GST range (US)	0.5 – 8.5	0.5 – 8.5	0.5 – 8.5	23.0 – 8.0
GST range (Other)	0.5 – 8.5	0.5 – 8.5	0.5 – 8.5	23.0 – 8.0
Band(s)	3.6	3.6	3.6	3.6
Flux density (Total, Jy)	0.00048	0.00023	0.003	0.00064
Flux (correlated, mJy)	0.33 ?	0.27 ?	1.3 ?	0.19 ?
RMS needed (mJy/beam)	0.017	0.017	0.017	0.017
Peak/RMS needed	5	5	5	5

(19) Preferred VLBI session or range of dates for scheduling, and why:
End of July or August to avoid various DSN commitments (ref. V. Altunin),
but must avoid LST range at Goldstone committed to Galileo, LST=20 ± 4.
Participation of both Y27 and Goldstone are critical to the proposed observations.

(20) Dates which are NOT acceptable, and why:
To allow supervision of phased array operations, first 2 weeks of June (AAS).
Last two weeks of August (IAU), unless DSN unavailable at any another time.

(21) Attach a self-contained scientific justification, not in excess of 1000 words.
Preprints or reprints will not be forwarded to the referees.

A brief description of the capabilities of the VLBA may be obtained by anonymous ftp from ftp.aoc.nrao.edu (146.88.1.103 if you do not use a name server), file pub/obssum.vlba.ps. Or, if you have the mosaic software available, use URL http://info.aoc.nrao.edu.

A brief description of the capabilities of the EVN may be obtained by ftp from astbo1.bo.cnr.it (137.204.51.1 if you do not use a nameserver), login VLBINFO, file EVN.STS.

Please include the full addresses (postal and e-mail) for first-time users or for those that have moved (if not contact author).

Scientific Justification

1. Motivation

The fundamental purpose of this proposal is to explore, *for the first time*, structures within a few A.U. of a forming star. The figure attached to this proposal shows a schematic diagram of the structures one might expect in the vicinity of such a star.

The diagram in the figure is based on a wealth of theoretical and observational work, carried out primarily over the past ten years (see Shu 1995). The current theoretical picture of low-mass star formation features an accretion disk around a young star, and an outflow from the star/disk system. The mass accretion rate of the system is only slightly higher than the mass outflow rate, so the lifetime of the accretion/outflow phase is thought to be long ($\sim 10^6$ yr). Many lines of observational evidence support this picture, including detection of jets and outflows from young stars (in optical continuum, optical shock-excited spectral lines, shocked H_2 emission, and molecular lines), and direct detection of large-scale (~ 100 A.U.) circumstellar "disks" (in mm spectral lines and reflected optical continuum light). These observations are incredibly impressive, but the rapidly accreting portion of circumstellar disks that we seek to study here is buried deep within the "disks" detected by connected-element interferometers and the Hubble Space Telescope.

To our knowledge, *no VLBI continuum observations* of very young pre-main-sequence stars have yet been carried out.[1] And, there is one very good reason for this: *almost* no high-brightness temperature emission is expected from these regions. There are, however, also two good reasons to be optimistic: 1) the VLA and other compact arrays have successfully detected compact emission from these objects (see Appendix A); and 2) recent theoretical models predict the existence of shock-ionized gas in both the disks and the outflows, either or both of which would have $T_B \sim 10^5$ K, which should be detectable on the shorter VLBA baselines.

The typical resolution achievable with the VLA, $\sim 0.4''$ with the A-array at 3.6 cm (e.g. Rodriguez *et al.* 1994), corresponds to a linear resolution of 55 A.U. at the distance to the Taurus star-forming clouds (~ 140 pc). With that kind of resolution, maps of PMS

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[1] VLBI has been successfully used to map out non-thermal continuum emission from highly time-variable pre-main-sequence (PMS) stars older than the ones we propose to observe here (e.g. Phillips *et al.* 1991; Phillips *et al.* 1993; Feigelson *et al.* 1994). The emission in those systems is thought to arise in solar-flare like events at the surface of the PMS object. This is *not* the emission we seek to detect, and the stars we have selected are expected to be too young to be magnetically active.

star-environments usually show resolved structures on scales ~ 2 beams. However, much of the observed flux is concentrated in an unresolved component (see the figure and Appendix A). Extrapolating the dust continuum from observations at shorter wavelengths falls short of these typical VLA cm-fluxes by as much as two orders of magnitude (see Mundy *et al.* 1993). In addition, the spectral index of the "excess" cm-wave emission is consistent with a bremsstrahlung source. Therefore, many who have observed the cm-emission from these sources with the VLA (e.g. Rodriguez *et al.* 1994; Wilner *et al.* 1996) propose that it orignates from ionized gas either associated with the accretion disk or with the wind from the young star, as shown schematically in the figure.

2. Expected Results and Their Value

If the cm-wave emission detected by the VLA is indeed free-free, then the obvious question to ask is: *what is its source?* This is the question this proposal seeks to answer. Theoretically, there are two main categories of possiblity. First, it is possible that all of the free-free flux observed by the connected-element interferometers is produced by copious amounts of spatially extended photo-ionized gas, which is characterized by $T_B \sim 10^4$ K. Second, it is possible that a significant fraction of the flux arises in compact, hot ($T_B \sim 10^5$), regions which are shock-ionized. These high-brightness-temperature shocked regions are predicted to exist under conditions where shock velocities are about 100 to 150 km s^{-1} (Neufeld and Hollenbach 1996). This range of velocities should be present, according to many independent theoretical models, at one or both of two distinct locations: in an annulus within the accretion disk, and/or in the outflow from the star.[2]

In either a disk- or an outflow-shock scenario, the exact location and extent of the shock-ionized gas (and hence the free-free emission) is determined by the details of the velocity field. Those "details," which refer to size scales $\lesssim$ a few A.U., differ greatly from theory to theory, but there are currently no observational constraints on size scales less than ~ 100 A.U. (see the figure).

There are two possible outcomes of this experiment:

- If compact $T_B \sim 10^5$ K regions do exist, we should detect free-free radio continuum with clear structure on scales of a few A.U. and below. These structures can then be interpreted within the confines of existing theoretical paradigms for low-mass star

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[2] The figure shows estimates for the scales assoicated with the shocked regions based on the estimates in Neufeld and Hollenbach 1996.

formation, which may need to be adjusted based on our observations.

- If the free-free flux does not come from compact high-T_B regions, we will not detect it in this experiment. We will then be able to say that the scale of the ionized gas producing the free-free emission is larger than the largest VLBA beam ($\sim 0.007''$) we will be able to synthesize, and smaller than the smallest VLA beam used to date ($\sim 0.3''$). This will constrain theoretical models to NOT produce the kind of compact, hot, shock-ionized gas we would have otherwise detected in our VLBA experiment. Models where all of the VLA-detected free-free arises in a photo-ionized jet from the star would then be favored.

As a by-product of using the phased VLA in our VLB array, we will also be able to construct highly sensitive maps of our sources at 3.6 cm with resolution $\sim 0.3''$. The specific sources to be observed, and their selection, are discussed in Appendix A. We choose to observe at 3.6 cm where the product of detector sensitivity and source flux density is maximized.

3. Technical Justification

We propose VLBA observations of four PMS stars, at 3.6 cm with the Southwestern array, VLA phased array, and Goldstone-70m antenna. The target sources are close in angle to extragalactic radio sources that shine through the Taurus and Perseus molecular cloud complexes. Specifically, HL Tau, XZ Tau, and L1551-IRS5 lie within 2° of the radio galaxy 0428+205, and NGC1333-IRAS4A lies within 2° of the quasar NRAO140. Both reference sources have nominal correlated fluxes of 0.2–0.5 Jy on milliarcsecond scales (Dallacasa et al. 1995; Morabito et al. 1986). We will re-measure their fluxes with VLA snapshots in advance of the VLBA observations. Two of the stars, HL Tau and XZ Tau are separated by about $20''$ ($\ll 1$ beam except at the phased array) and may be observed simultaneously (except at the VLA, where will use two phased sub-arrays), though each will require a separate pass through the correlator.

To obtain adequate sensitivity, we will observe in mode 256-8-2, which provides 64 MHz total bandwidth (8×8 MHz). For the VLBA alone, a 5 hour integration yields a 1σ noise level of 87 μJy, assuming 5 antennas (FD, LA, PT, KP, and OV), a 300 Jy SEFD, 80% duty cycle on the target source, and 20% digitization/processing loss. The addition of the phased array to the VLBA reduces the noise by a factor of 2.8, and the further addition of the Goldstone 70-m reduces the noise by an additional factor of 1.8, to 17 μJy. The flux density of the stars at the highest previously obtained angular resolution is at least 0.2 mJy, which would provide a 12σ detection if concentrated in a single unresolved source. The 1σ

noise in the maps will be equivalent to about $T_B = 1 - 1.3 \times 10^4$ K in a square patch 5-6 mas on a side. The synthesized beam for variance-weighting of the (u,v)-data and natural weighting in imaging is about 9×4 mas. Since the maximum expected source brightness temperatures ($\sim 10^5$ K) are low in comparison with typical VLBI sources, participation of both the phased array and Goldstone-70m are *critical.*

Each 5 hour integration for each source will fit on one VLBA tape. (HL Tau and XZ Tau are considered together.) To observe 3 fields on the sky, we would need 3 tapes and 3×6-hour tracks. The additional hour is needed to accomodate slew times, and phasing tests of the VLA.

References

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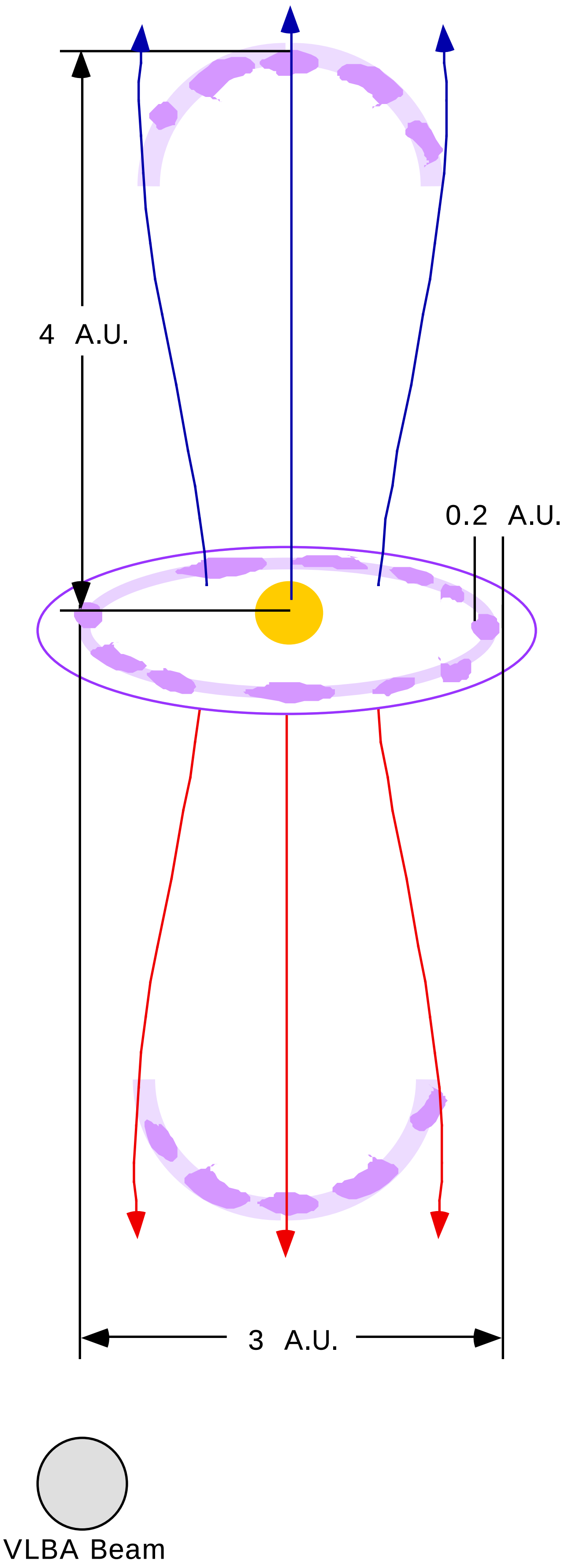
Appendix A: Source Selection

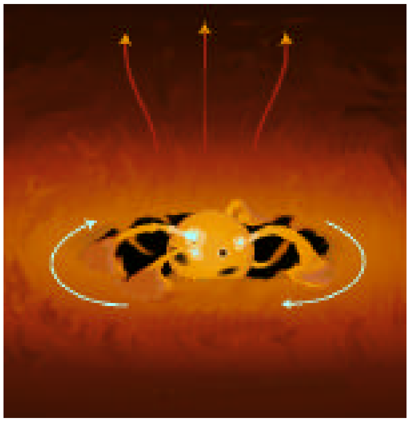
We plan to observe four of the most heavily-studied pre-main-sequence objects known: NGC 1333 IRAS 4, HL Tau, XZ Tau, and L1551 IRS 5. According to numerous prior observations of these sources, including the ones listed in the table below, these stars are all likely to have masses and mass accretion rates in the range considered in the theoretical models discussed by Neufeld & Hollenbach (1996). The table lists an “SED Class” associated with the Spectral Energy Distribution of each source. For reference, Class 0 objects are thought to be the youngest, and Class III the oldest, pre-main-sequence stars. Weak-line T-Tauri Stars (WTTS), which are Class III and older, have already been detected with VLBI (see footnote on p. 1). The cm-emission from WTTS comes principally from stellar magnetic activity, not shocks. Our sources should be too young to be magnetically active.

Source	λ cm	Flux [mJy(/beam)]				Observed with	Resl'n. arcsec	Reference	SED Class	Comments
		Peak	1σ	Total	1σ					
HL Tau	**1.3**					VLA-A	0.3 to 0.4	Rodriguez et al. 1994	II	dominated by dust (from disk?)
HL Tau	**3.6**	0.27		**0.52**	0.02	VLA-A	0.3 to 0.4	Rodriguez et al. 1994	II	dominated by free-free (from flow?)
HL Tau	**3.6**	0.39	0.04	**0.44**	0.04	VLA-B	0.5	Wilner et al. 1996	II	outer antennas only; free-free origin
HL Tau	**6**			**0.25**		VLA-C	0.5	Brown et al. 1985	II	according to Evans et al. 1987
HL Tau	**6**	0.28	0.03			VLA-B	0.9	Wilner et al. 1996	II	outer antennas only; free-free origin
XZ Tau	**3.6**	0.27		**0.23**	0.01	VLA-A	0.3 to 0.4	Rodriguez et al. 1994	III	
L1551-IRS 5	**2**	<1.8				VLA-A/C		Bieging et al. 1984	I/II	see also map in Cohen et al. 1982
L1551-IRS 5	**2**			**0.10**	0.01	VLA-A	0.5	Evans et al. 1987	I/II	
L1551-IRS 5	**2**	0.98	0.14			VLA-A	0.15	Rodriguez et al. 1986	I/II	proposed heated inner edge of annulus, rather than binary
L1551-IRS 5	**6**	1.70	0.15	**3.00**	0.30	VLA-A/C		Bieging et al. 1984		exhibits "core/halo" map; halo=ionized jet?
L1551-IRS 5	**6**	1.40	0.07	**5.00**		VLA-A	0.5	Evans et al. 1987	I/II	
NGC 1333 IRAS 4B	**1.3**	0.64	0.09	**1.80**		VLA-B	0.6	Mundy et al. 1993	0/I	
NGC 1333 IRAS 4B	**2**	<.3	0.10			VLA-B	0.4	Mundy et al. 1993	0/I	
NGC 1333 IRAS 4B	**3.6**	0.07	0.02	**0.07**		VLA-A and VLA-B	0.5 to 1	Mundy et al. 1993	0/I	
NGC1333 IRAS 4A	**1.3**	1.80	0.09	**5.90**		VLA-B	0.6	Mundy et al. 1993	0/I	
NGC1333 IRAS 4A	**2**	0.70	0.10			VLA-B	0.4	Mundy et al. 1993	0/I	
NGC1333 IRAS 4A	**3.6**	0.19	0.02	**0.64**		VLA-A and VLA-B	0.5 to 1	Mundy et al. 1993	0/I	

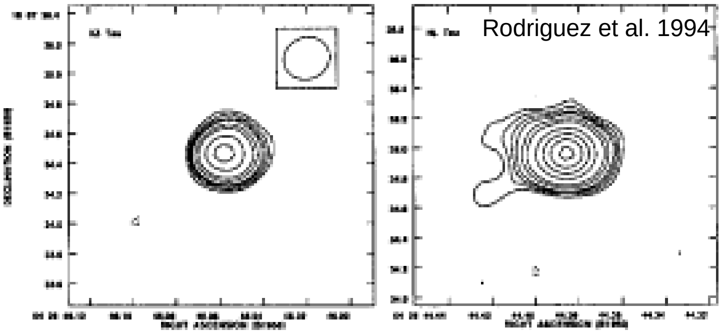
Shocked Gas in the Vicinity of a Forming Star



The purple shaded regions at **left** show theoretically predicted locations of shock-ionized gas, which should have T_B~10^5 K. These regions can (and possibly do) occur in both an accretion disk around the forming star, as well as in the outflowing gas. The **color inset below** shows Patrick Hartigan's artist's conception of the simultaneous accretion and outflow associated with a forming star.



VLA observations (**below**) of PMS stars detect free-free emission, but cannot resolve any of the structures shown at left.



Rodriguez et al. 1994

FIG. 2.—Cleaned, natural-weight VLA maps of XZ (*left*) and HL Tau (*right*) at 3.6 cm. Contours are −4, −3, 3, 4, 5, 6, 8, 10, 15, 20, 25, and 30 times 9 μJy beam^{-1}, the rms noise of the map. The half-power contour of the beam is shown in the XZ Tau map.