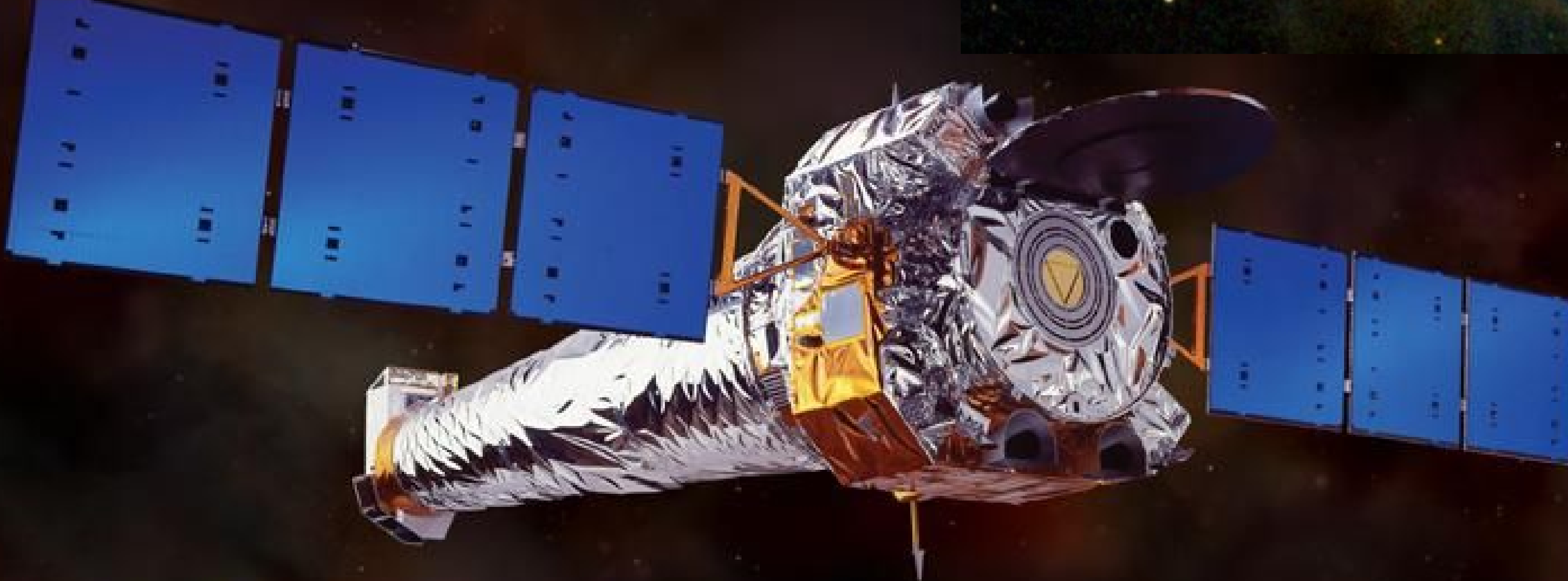
Radio, X-ray, and Infrared Variability of Young Stellar Objects in the *Coronet* Cluster



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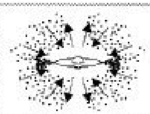
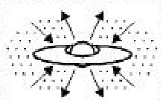
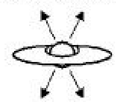
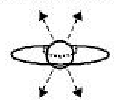
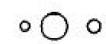
Outline

- Introduction
  - Radio and X-ray Emission from YSOs
- The *Coronet* Cluster
  - 1998 multi-epoch VLA observations
  - 2000-2003 archival (*Chandra* & XMM-*Newton*) X-ray data, covering >150 ksec in total
  - Outlook: *simultaneous* multi-wavelength observations

SMARTS

Radio, X-ray, and NIR emission from protostars

PROPERTIES	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
SKETCH					
AGE (YEARS)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-RAY	?	Yes	Strong	Strong	Weak
THERMAL RADIO	Yes	Yes	Yes	No	No
NON-THERMAL RADIO	No	Yes	No ?	Yes	Yes

circumstellar material observable e.g. in the NIR

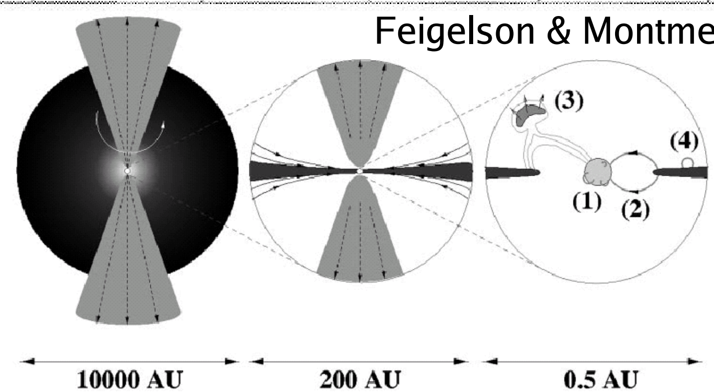
magnetospheric bremsstrahlung and/or accretion (e.g. Kastner et al. 2004)

e.g. from shock-induced ionisation, easily optically thick !

e.g. gyrosynchrotron, quickly variable, polarized

Feigelson & Montmerle (1999)

- connection to the different evolutionary stages of protostars is still poorly understood



- X-ray *and* radio emission probe the innermost regions around YSOs

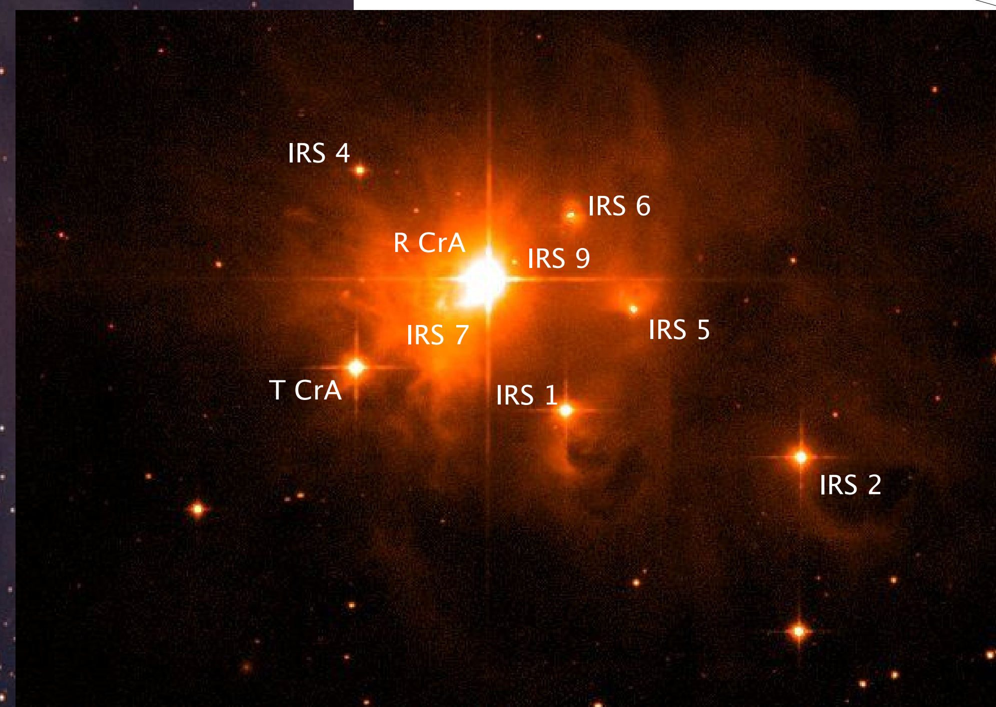
Multi-wavelength variability of protostars

- variability of protostars has mostly been studied at a single wavelength of the electromagnetic spectrum
- little is known about the *relationship* of radio, X-ray, and near infrared variability of protostars
- processes are poorly understood
- few *simultaneous* multi-wavelength observations
  - Bower (2003): serendipitous discovery (WTTS)
  - systematic attempts: Feigelson et al. (1994), Guenther et al. (2000) (single TTS), Gagné et al. (2004) (no class 0/I X-ray- and radio-detected)

The *Coronet* Cluster

R Coronae Australis Complex (Detail) (MPI/ESO 2.2-m + WFI)

ESO PR Photo 25b/00 (6 October 2000)



Wilking et al. (1997), *K'*

d = 150 pc

The *Coronet* at NIR wavelengths

	Source	L_* $L_\odot$	$E(H-K)$	A_V mag	L_{acc} $L_\odot$
x	IRS2	4.3 ± 1.5	1.3 ± 0.2	20 ± 3	7.7 ± 2.5
x	IRS5a	1.6 ± 0.5	2.9 ± 0.2	45 ± 3	~0.4
	IRS6a	0.5 ± 0.2	1.9 ± 0.3	29 ± 5	<0.1
x	HH100 IR (IRS 1)	3.1 ± 0.9	1.9 ± 0.2	30 ± 3	12 ± 2
	IRS3	0.3 ± 0.1	0.2 ± 0.2	10 ± 3	<0.1

IRS1 is the youngest source. IRS2 and IRS5a have about the same age in spite of their different accretion properties.
(variable accretion ?)

Nisini et al. (2005)

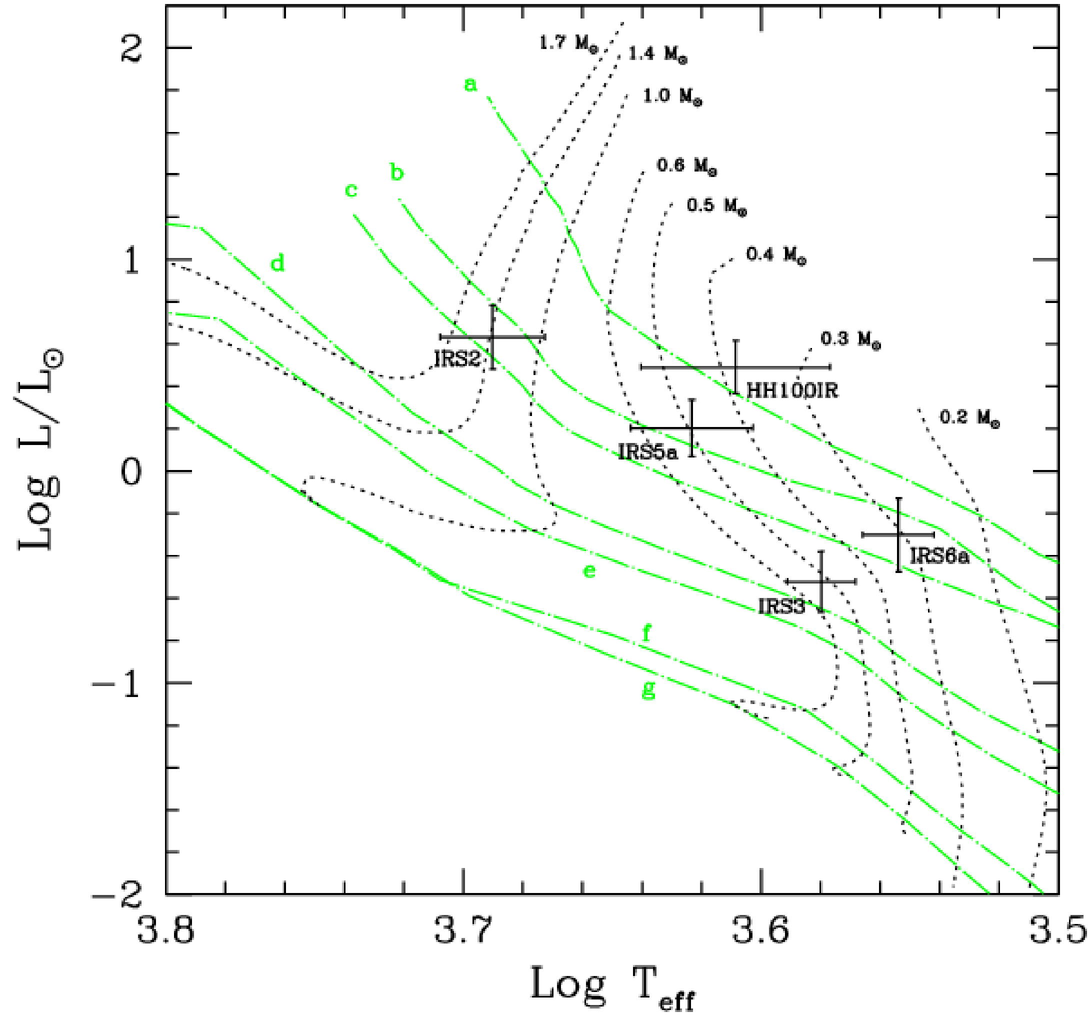
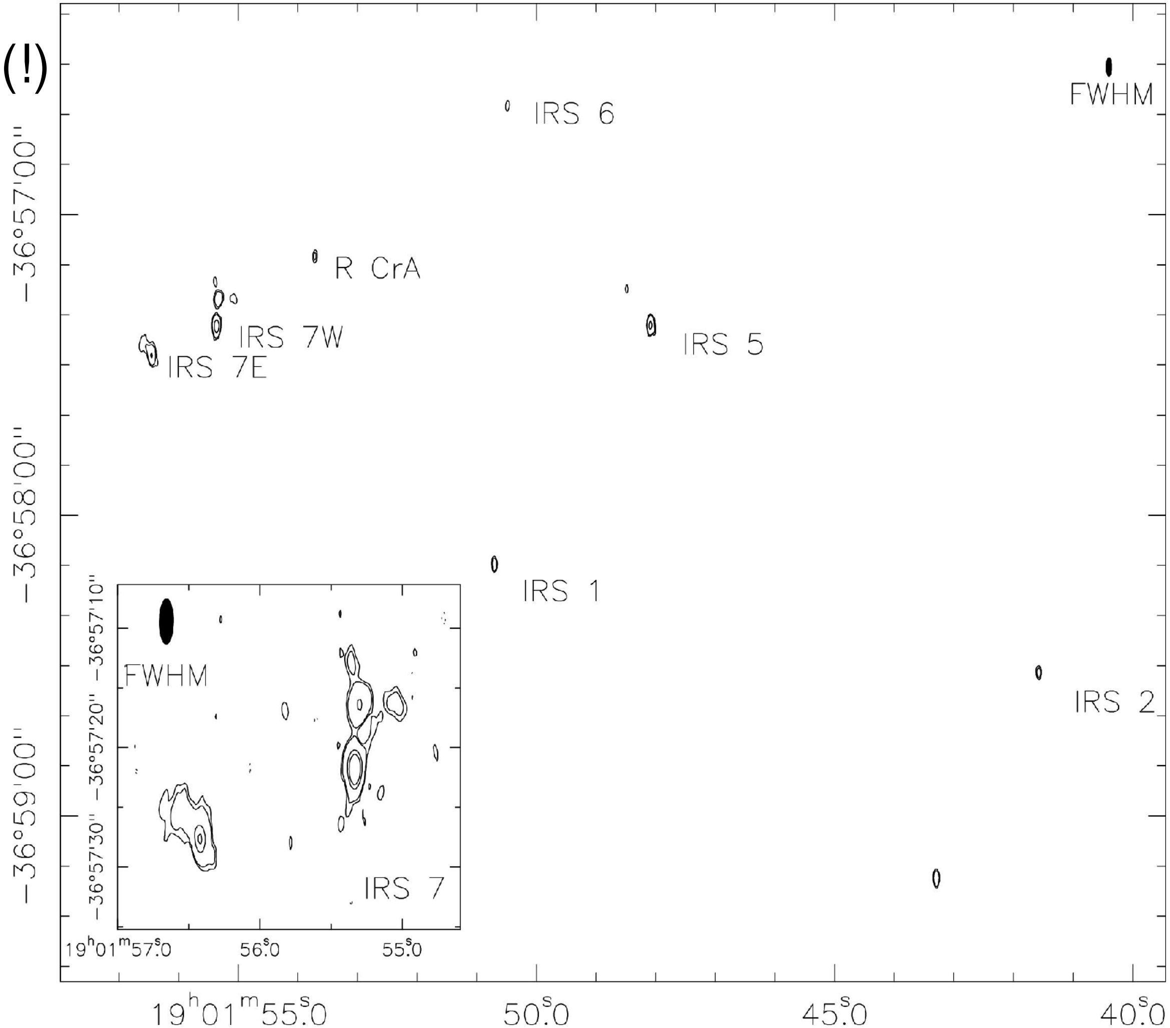


Fig. 11. HR digram of the R CrA sources with T_{eff} and stellar luminosity derived from the analysis of the medium resolution IR spectra. Evolutionary tracks (short dashed lines) and isochrones (dot-dashed lines) from D'Antona & Mazzitelli (1997) are shown for stellar masses between 0.2 and 1.7 $M_\odot$. Isochrones are reported for **a)** 10^5 yr, **b)** 5×10^5 yr, **c)** 10^6 yr, **d)** 5×10^6 yr, **e)** 10^7 yr, **f)** 5×10^7 yr and **g)** 10^8 yr.

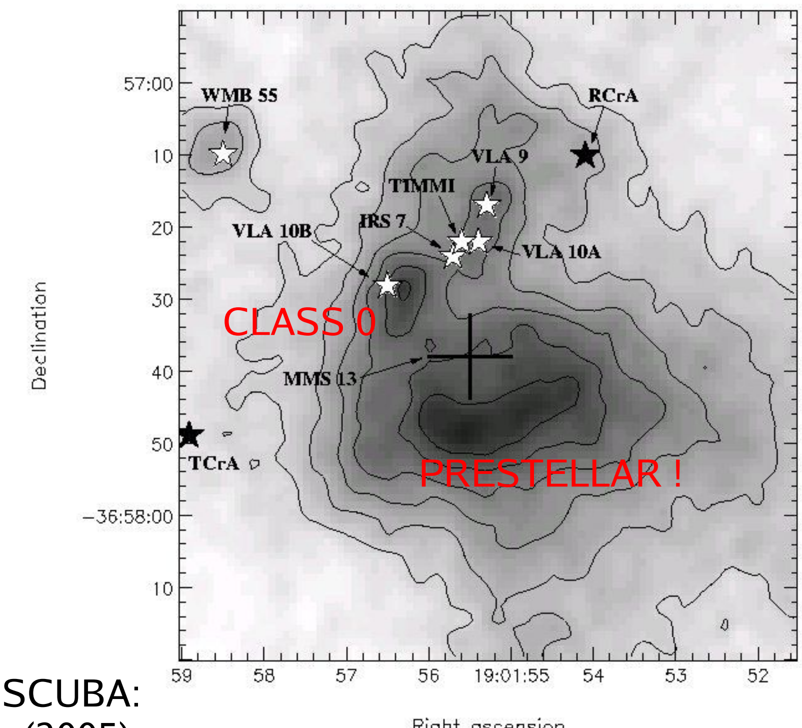
Radio Emission from the *Coronet*

(!)



1998 VLA 3.6 cm data, integration of 5x2h

previous studies by
Brown (1987)
Suters et al. (1996)
Feigelson et al. (1998)
Choi & Tatematsu (2004) [IRS 7]

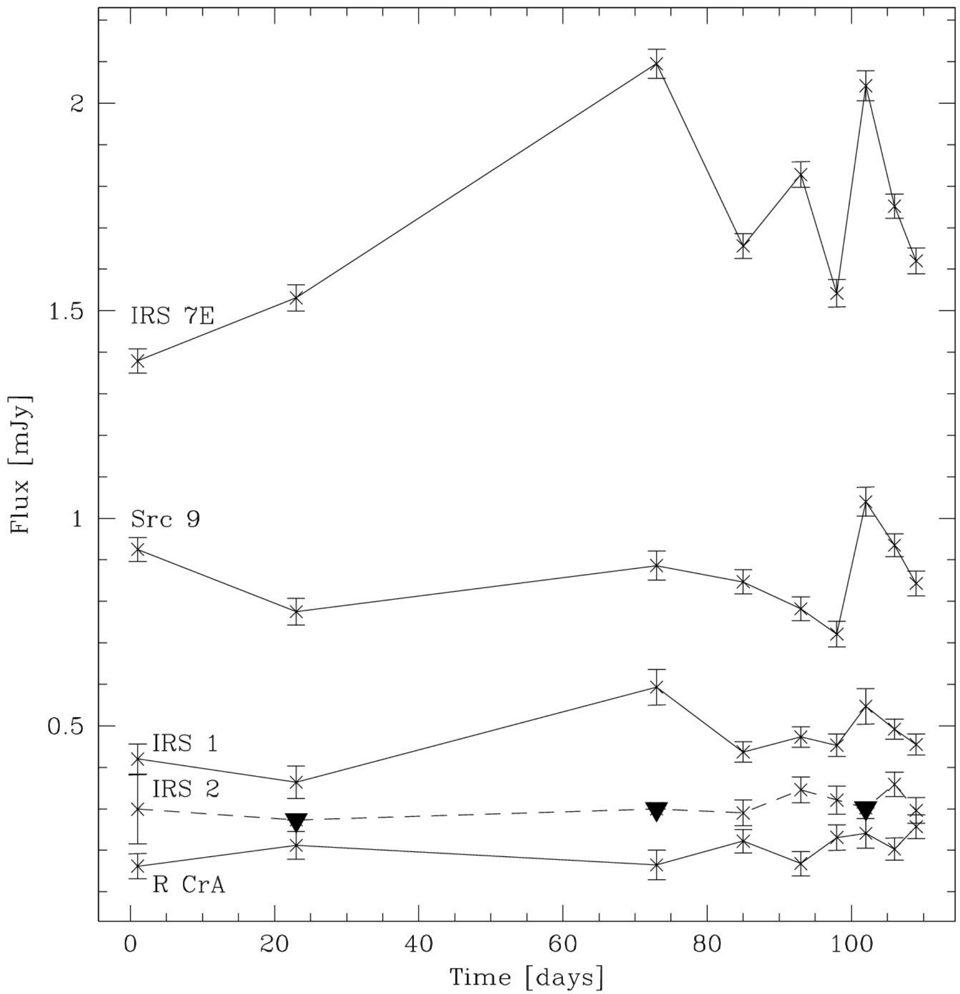


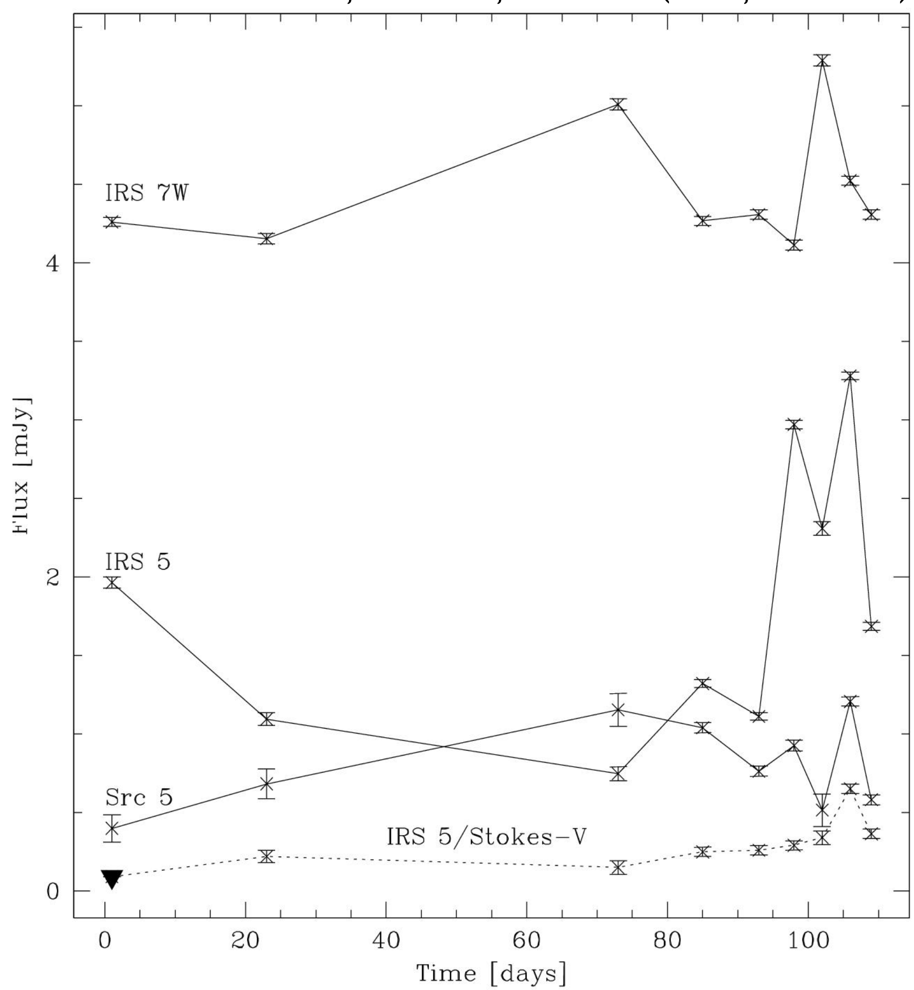
analyzed 9 epochs of 1998 VLA data spanning nearly four months

450 mu SCUBA:
Nutter et al. (2005)

Radio Emission from the *Coronet*

Forbrich, Preibisch, & Menten (2005, submitted)

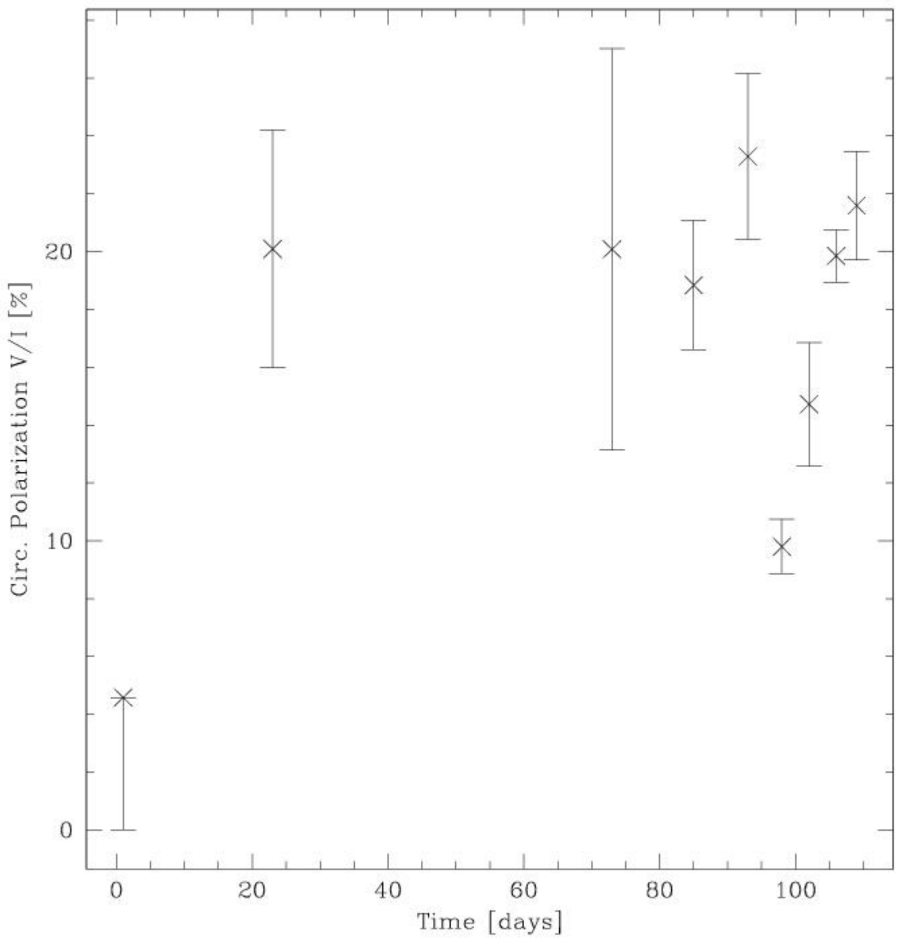




BD?

9 epochs of 1998 VLA data

Radio Emission from the *Coronet*



Forbrich, Preibisch, & Menten (2005, submitted)

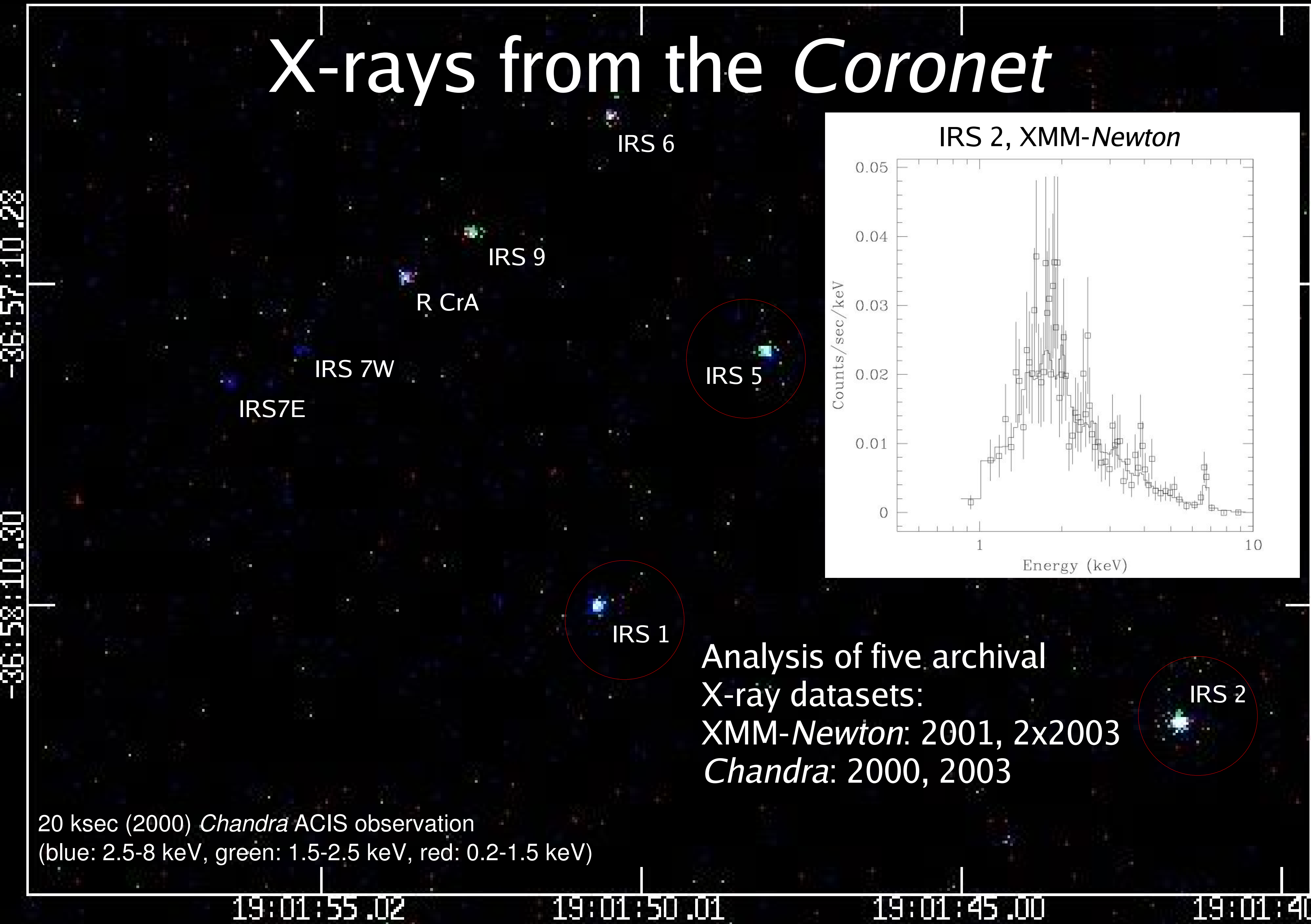
The circular polarisation of IRS5 is highly variable.

see also the discovery paper “Circularly Polarized Radio Emission from an X-Ray Protostar”

(Feigelson, Carkner, & Wilking, 1998)

9 epochs of 1998 VLA data

X-rays from the *Coronet*



Analysis of five archival X-ray datasets:
XMM-*Newton*: 2001, 2x2003
Chandra: 2000, 2003

20 ksec (2000) *Chandra* ACIS observation
(blue: 2.5-8 keV, green: 1.5-2.5 keV, red: 0.2-1.5 keV)

Spectral analysis of the class I protostars IRS 1, 2, and 5

Signs of temporal evolution ?

Forbrich, Preibisch, & Menten (2005, submitted)

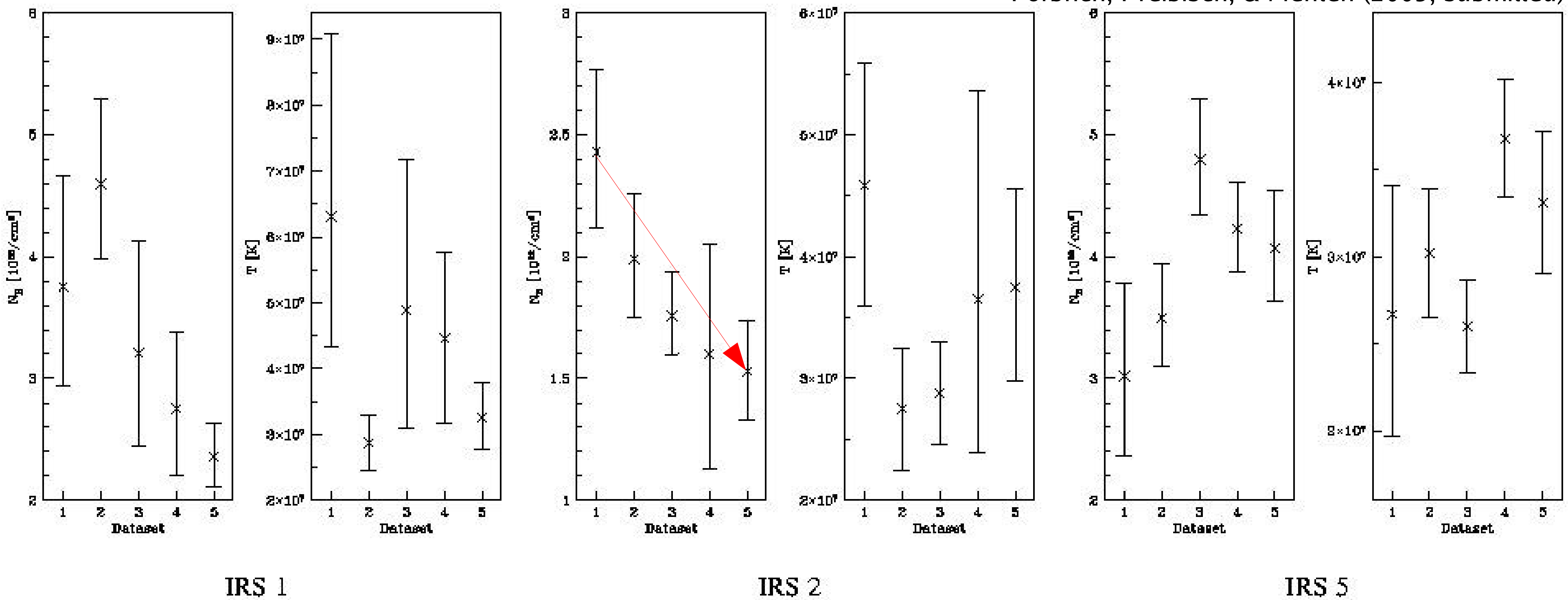


Fig. 7. Results of fitting **XSWABS×XSAPEC,** fit parameters N_H and kT. Abundances set to values determined from best spectra. Errorbars are 3σ. The X-ray datasets are numbered according to Table 2. The NIR-determined N_H column densities from Nisini et al. (2005) are 6×10^{22} cm^{-2} (IRS 1), 4×10^{22} cm^{-2} (IRS 2) and 9×10^{22} cm^{-2} (IRS 5).

Spectra can be explained by highly absorbed hot plasma emission (several 10MK).

Spectral analysis of the class I protostars IRS 1, 2, and 5

The extinction problem

Source	N_H(NIR)[a] $[10^{22}\ \mathrm{cm}^{-2}]$	N_H(X-ray) $[10^{22}\ \mathrm{cm}^{-2}]$
IRS 2	4.0 ± 0.6	1.9 ± 0.4
IRS 5	9.0 ± 0.6	3.9 ± 0.7
IRS 1	6.0 ± 0.6	3.3 ± 0.9

[a] A_V (from Nisini et al. 2005) converted into N_H using $N_H[\mathrm{cm}^{-2}] \approx 2 \times 10^{21} \times A_V[\mathrm{mag}]$, see text

The values for the column densities are all at around *half* the values derived from NIR colors, as observed towards some other YSOs:

L1551IRS5 – Bally et al. (2003)
EC95 – Preibisch (2003a)
SVS16 – Preibisch (2003b).

Maybe the NIR and X-ray emission come from detached regions ?

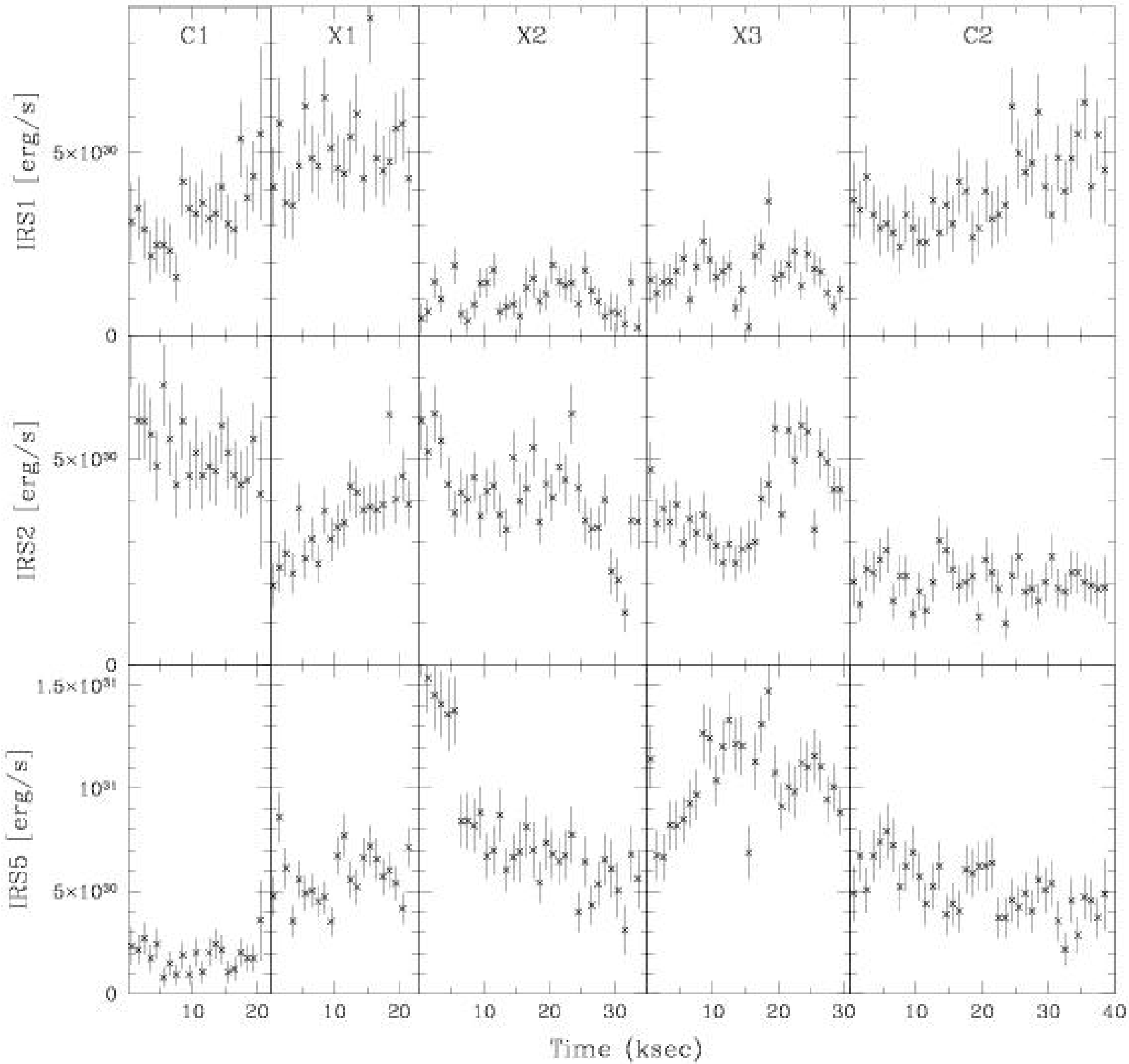
- X-rays from jet shocks close to the protostar ?
- X-rays scattered towards the observer ?
- huge coronal structures ?

Luminosity curves for IRS 1, 2, 5

Forbrich, Preibisch, & Menten (2005, submitted)

Source	L_{bol}^{a}	L_X	$\log(L_X/L_{bol})$
	$L_\odot$	10^{-3} $L_\odot$	
IRS 2	16	0.93	−4.2
IRS 5	4	1.70	−3.4
IRS 1	19	0.75	−4.4
R CrA	132	0.18	−5.9

[a] scaled to $d = 150$ pc from Wilking et al. (1992), for R CrA directly from Lorenzetti et al. (1999)

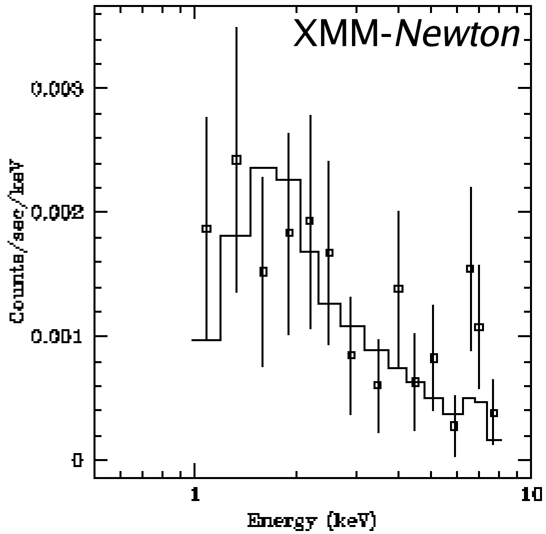


Oct 00 Apr 01 Mar 03 Jun 03

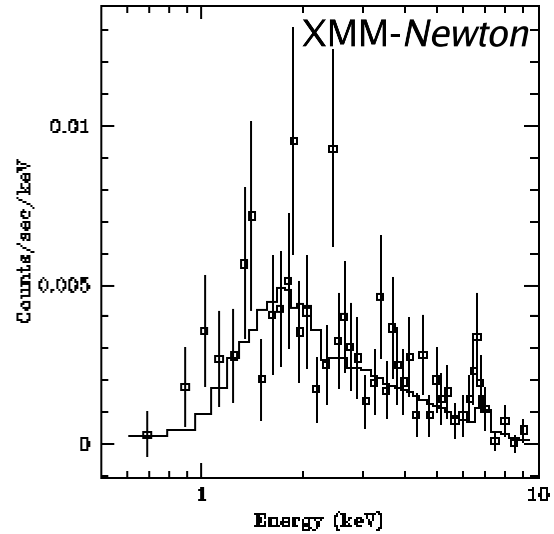
IRS5 is again the most variable source.

The Herbig Ae star R CrA

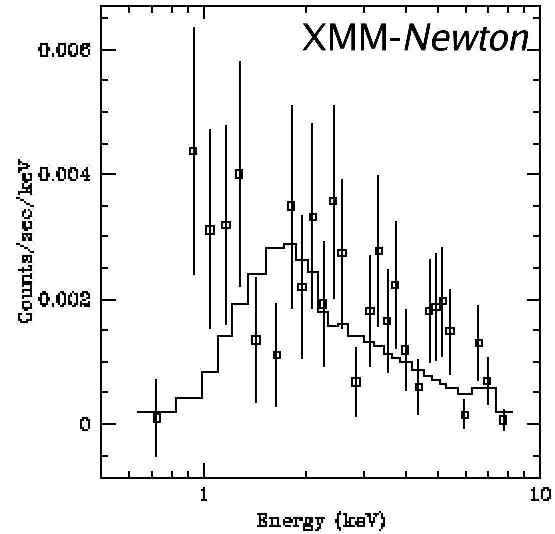
Forbrich, Preibisch, & Menten (2005, submitted)



X1



X2



X3

R CrA has X-ray emission from *very hot* plasma (100 MK !), but no corona and no strong stellar wind...
Takami et al. (2003) find some evidence for the presence of a companion separated by only 0.1” (i.e. only 10-15 AU).

Main Results

- IRS5 shows highly variable nonthermal radio emission with changes in its polarization, also variable X-ray emission
- X-ray spectra of class I protostars IRS 1,2,5 can be explained by absorbed emission of hot plasma (several 10 MK)
- the high absorbing column densities (several 10^{22} cm^{-2}) are at about half the values derived from NIR colors (the *extinction problem*)
- towards the Herbig Ae star R CrA, surprisingly hot plasma emission (100 MK!) was observed, possibly due to a companion
- **the next step**: *simultaneous* observations in August 2005 with R. Neuhäuser (Jena), B. Posselt (MPE/Jena), and F. Walter (SUNY)

S M A R T S