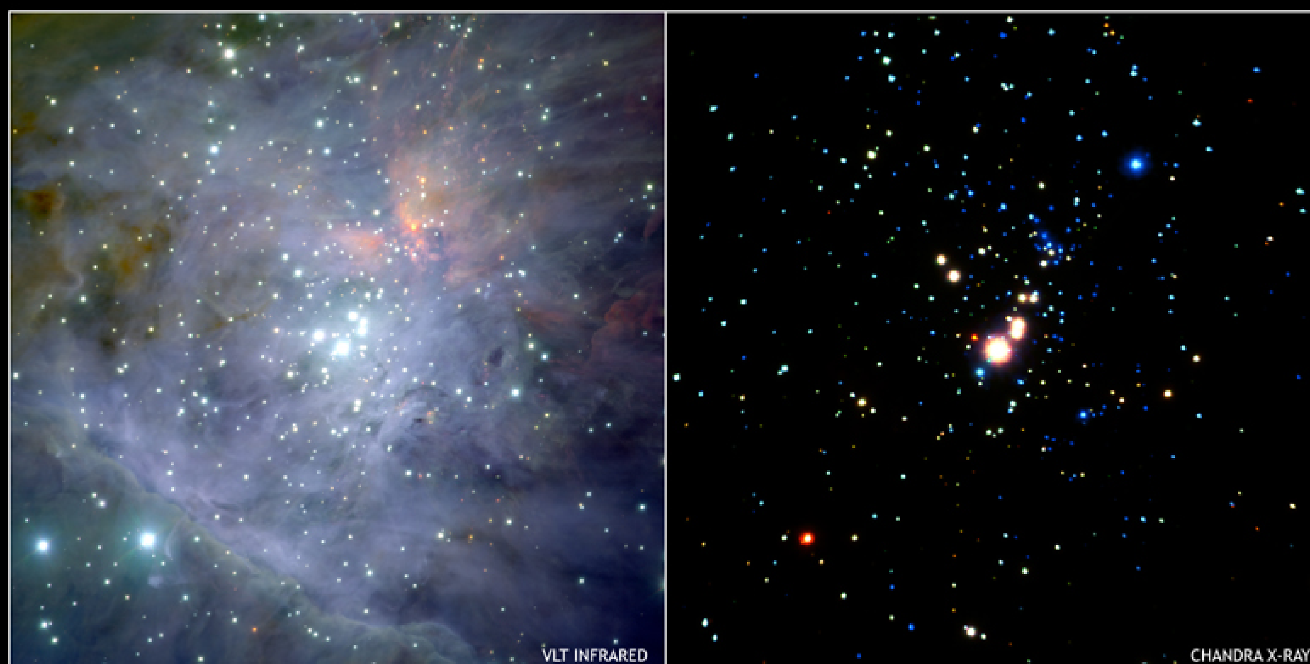
High-energy emission from the ONC – the radio and X-ray views

Jan Forbrich



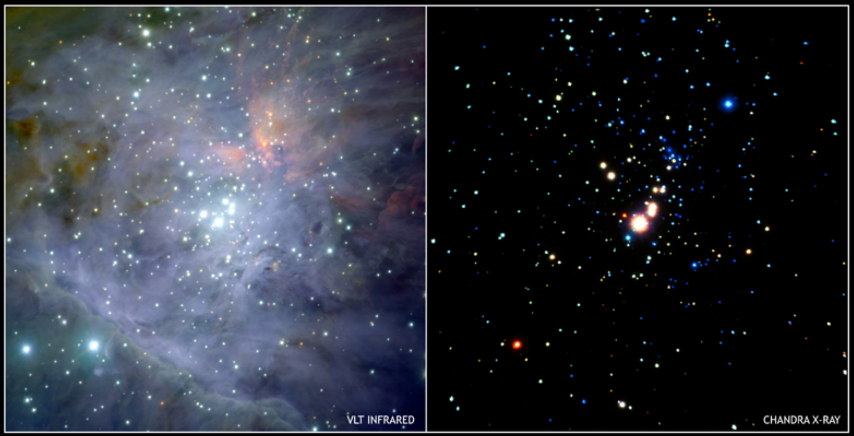
universität wien
VIENNA NOW OR NEVER
Smithsonian Astrophysical Observatory

Outline

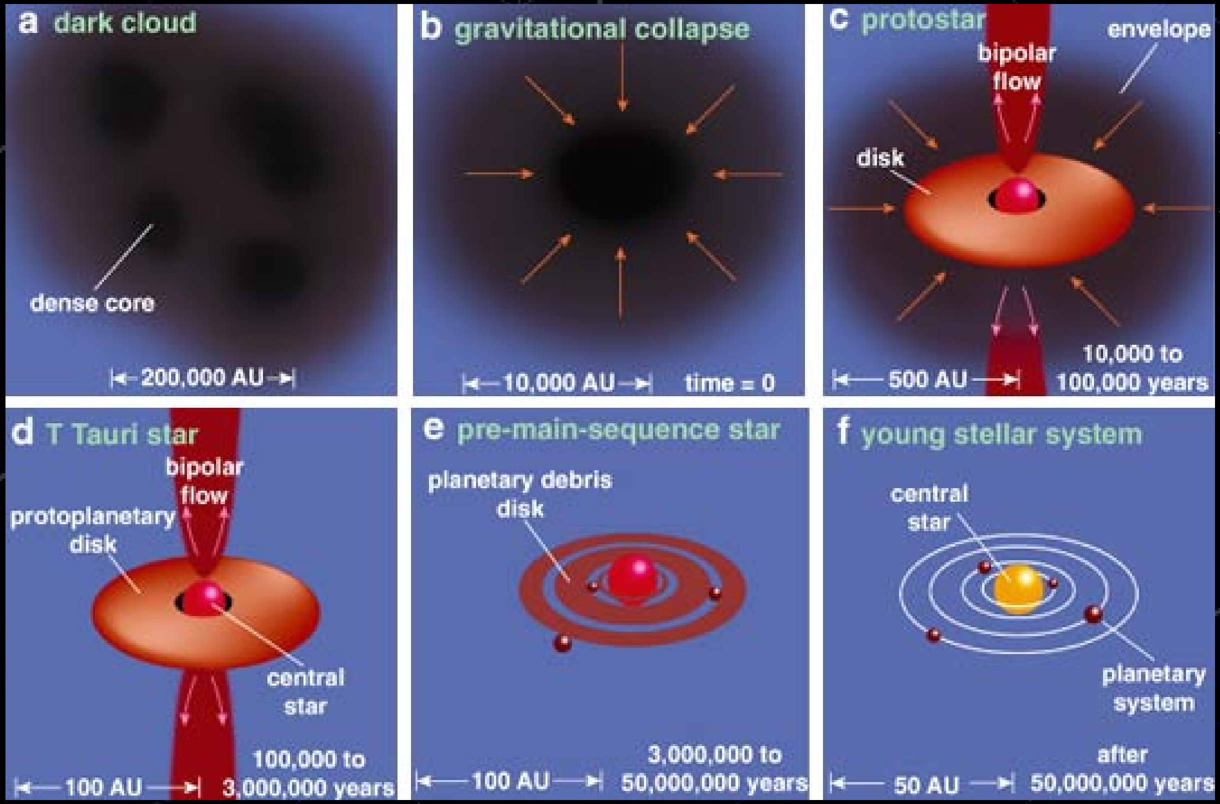
- Introduction: Emission mechanisms
- The X-ray view
- The … radio view
- Their combination
- Outlook: time-domain radio astronomy of stars

Very different object classes...

- Massive stars
- Young Stellar Objects
- Brown dwarfs

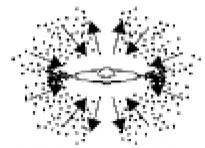
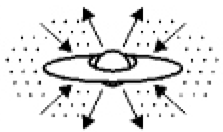
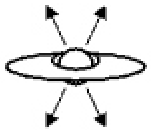
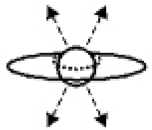
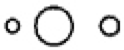


Low-mass star formation



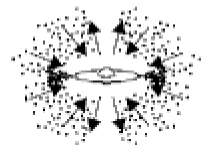
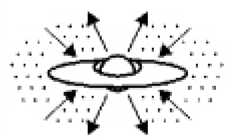
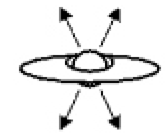
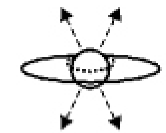
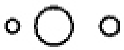
Greene (2001)

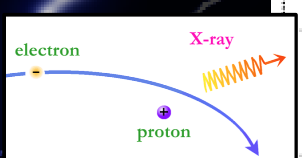
Low-mass star formation

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

Feigelson & Montmerle (1999)

Low-mass star formation

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 (e.g., free-free emission)	Yes	Yes	Yes	No	No
Nonthermal radio (e.g., gyrosynchrotron emission)	No	Yes	No ?	Yes	Yes



...only 2 sources!

Feigelson & Montmerle (1999)

Observations of *nonthermal* radio emission

Process: Gyrosynchrotron radiation

Identified by: Polarization, spectral index, rapid variability, high brightness temperature

Current problem: weak sources, measurement at single frequency

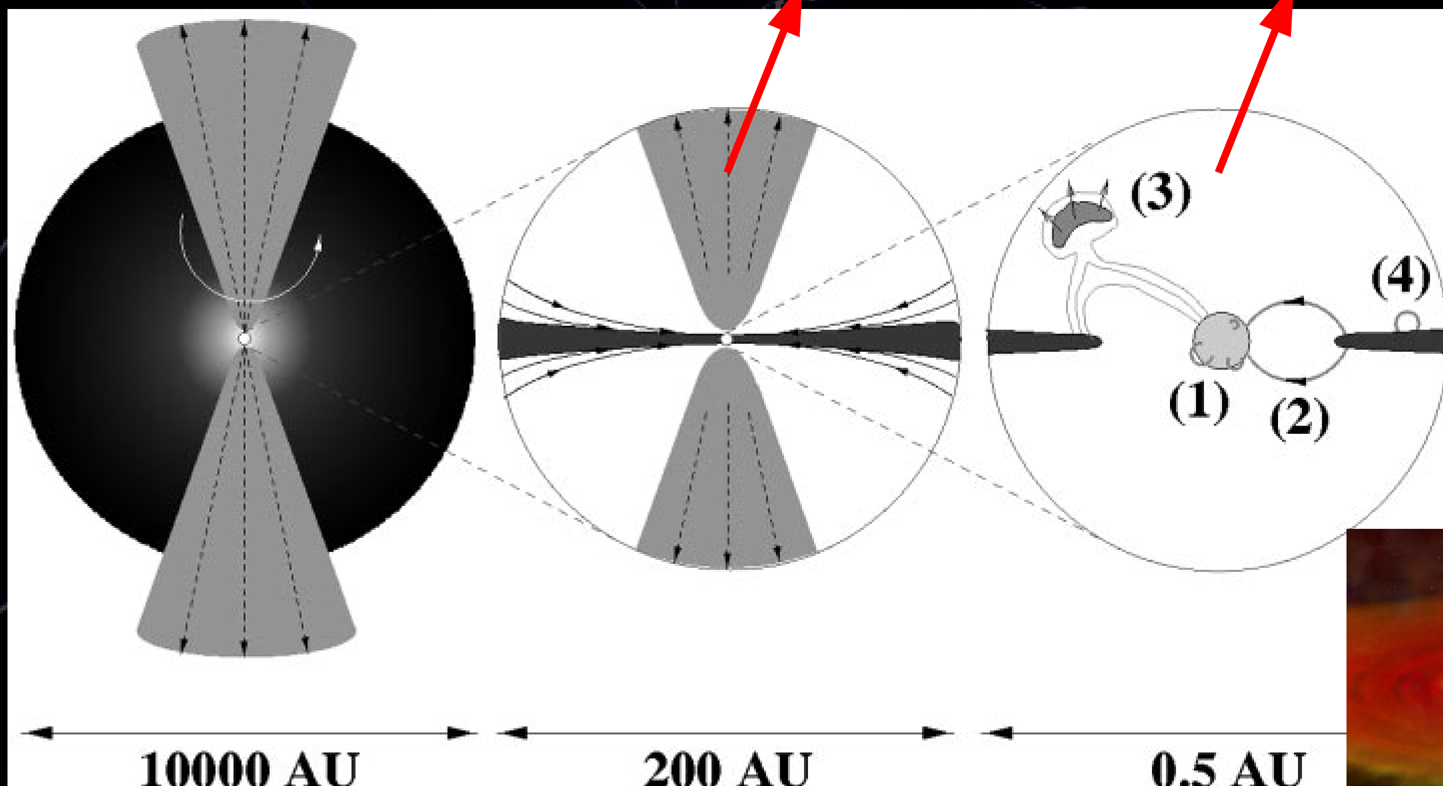
► Best evidence for nonthermal radiation requires high S/N – often not the case.

► Difficult to constrain the emission processes of many weak sources.

Low-mass star formation

thermal radio

(thermal) X-rays,
***nonthermal* radio**

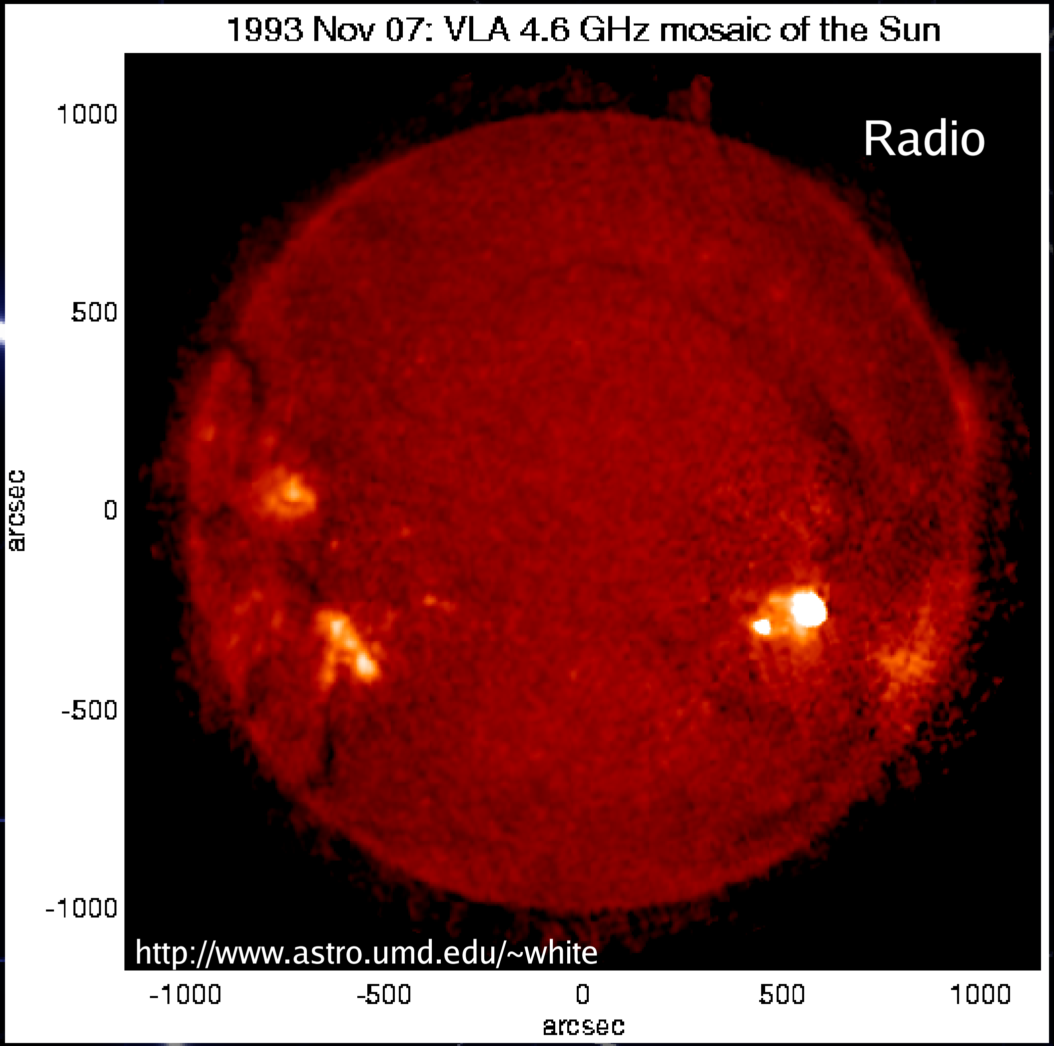


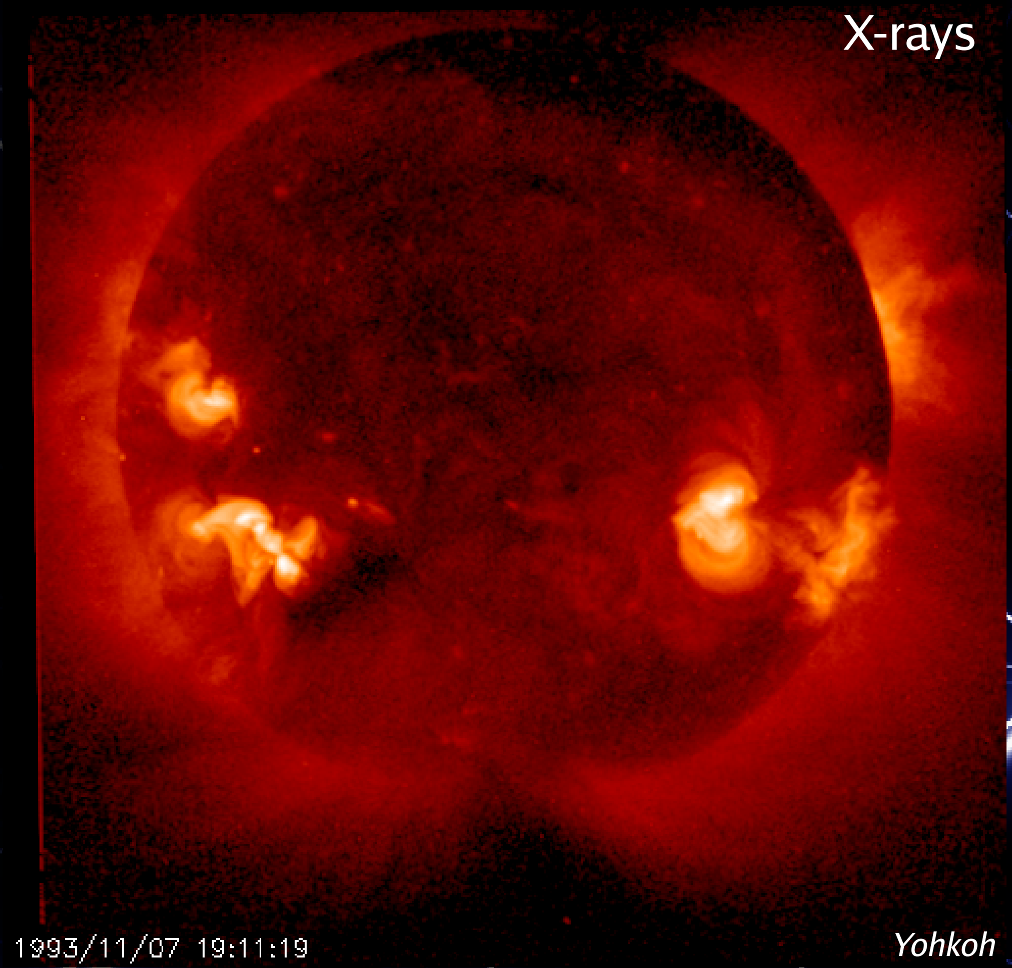
Feigelson & Montmerle (1999)

NASA/CXC/M.Weiss

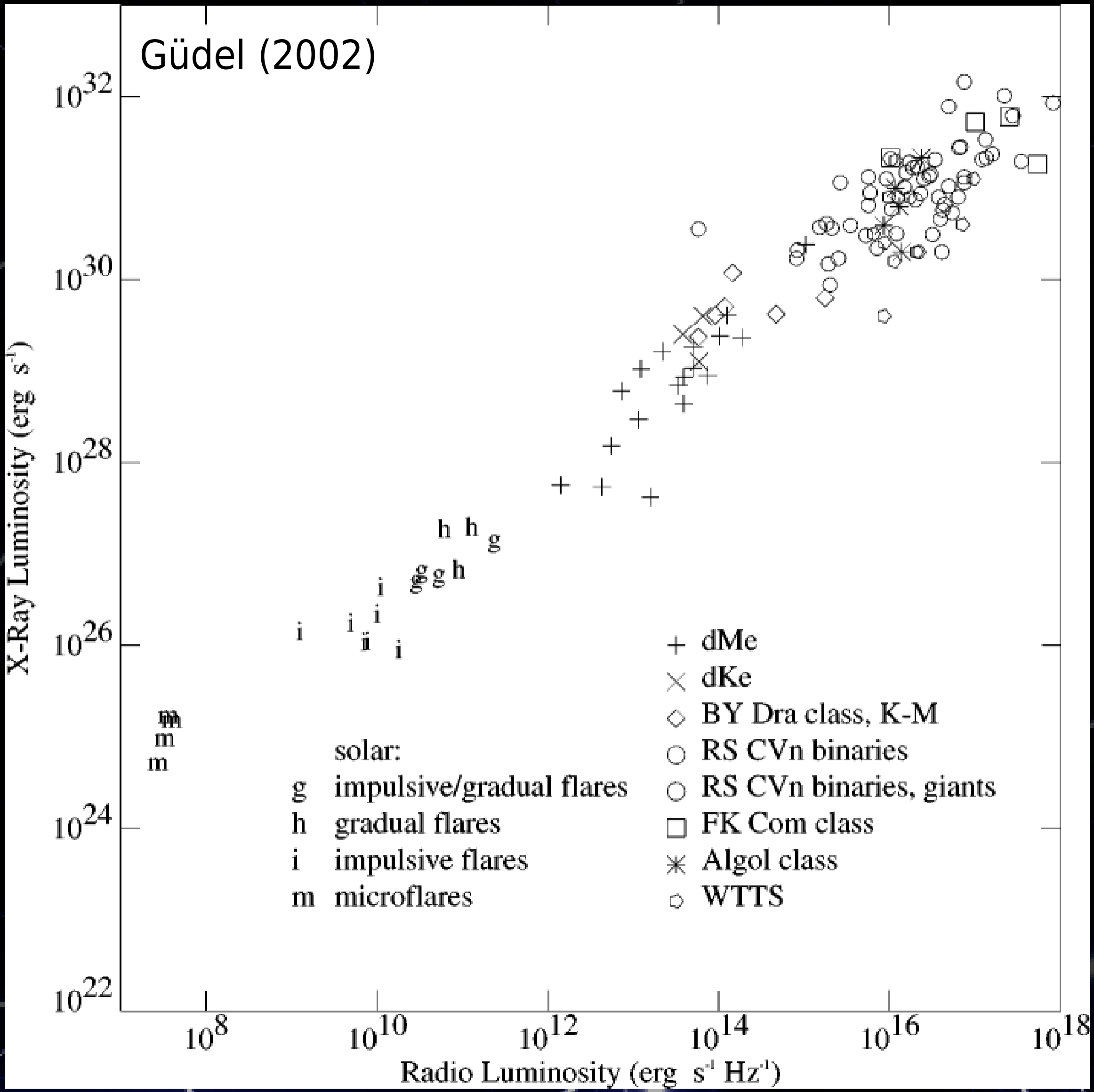
X-rays *and* nonthermal radio emission probe the **innermost vicinities** of protostars, but currently only radio observations offer high angular resolution (VLBI).

The solar paradigm



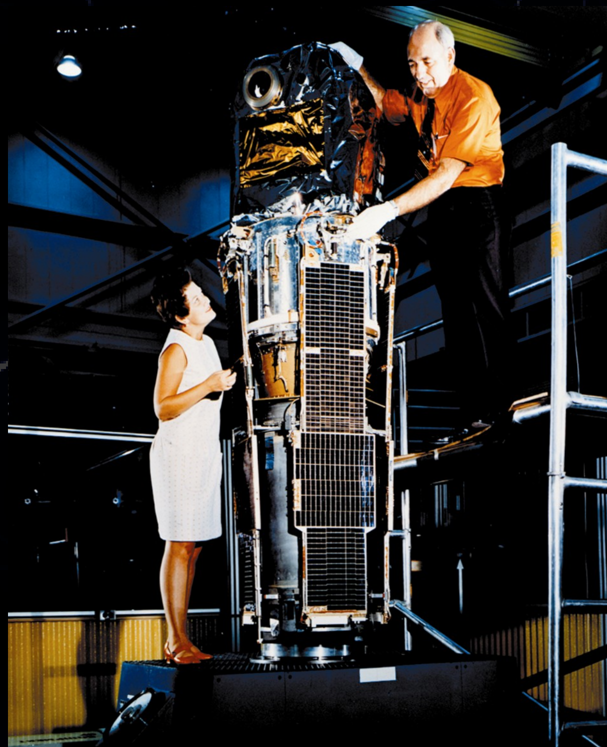


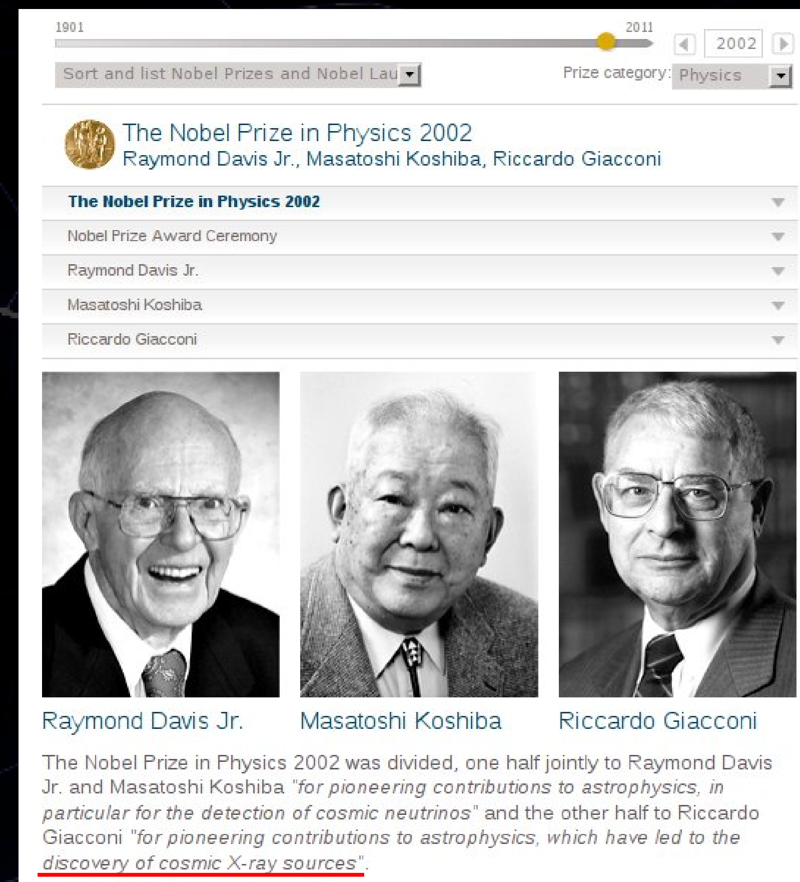
The X-ray radio connection



The Orion Nebula Cluster: the X-ray view

(leaving out high-resolution spectroscopy)





THE *UHURU* CATALOG OF X-RAY SOURCES

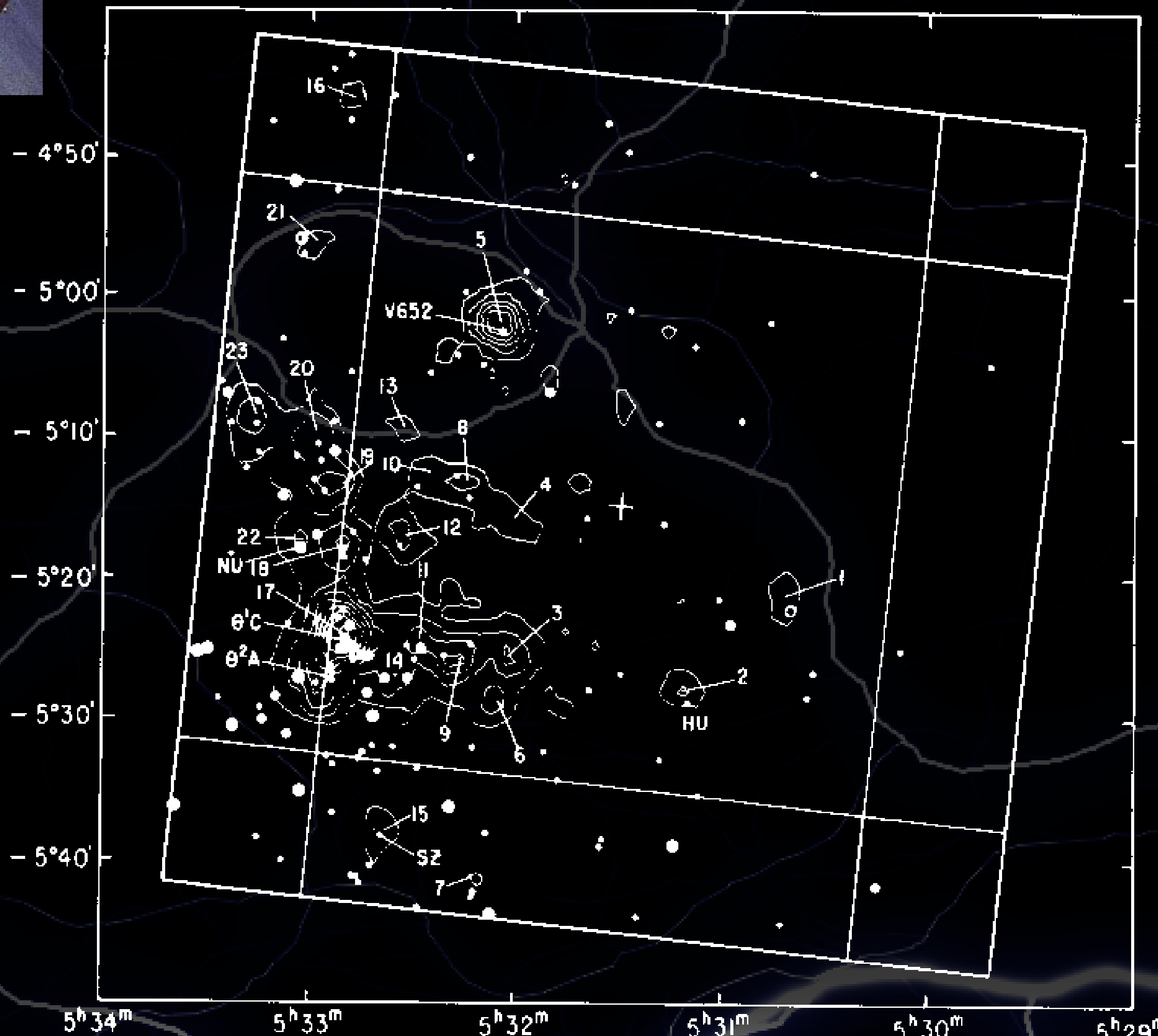
R. Giacconi, S. Murray, H. Gursky, E. Kellogg,
E. Schreier, and H. Tananbaum
American Science & Engineering, Cambridge, Massachusetts
Received 1972 May 4

ABSTRACT

A catalog of X-ray sources observed with the *Uhuru* satellite is presented. About 70 days of data have been analyzed for this catalog resulting in 125 sources. Approximately two-thirds of the sources are located within ±20° of the galactic plane. Some of the sources at higher galactic latitudes are identified with known extragalactic objects. Most of the strong sources near the galactic plane are found to be variable.

2U 0525−06 . . .	5 25 12 −6 7 12 81.30 −6.12	208.75 −21.39	5 42 48 −4 0 0 85.7 −4.0	5 14 48 −7 6 0 78.7 −7.1	5 15 36 −7 24 0 78.9 −7.4	5 44 24 −4 12 0 86.1 −4.2	2.700	3.8 ± 0.4	M42? Orion radio nebula?

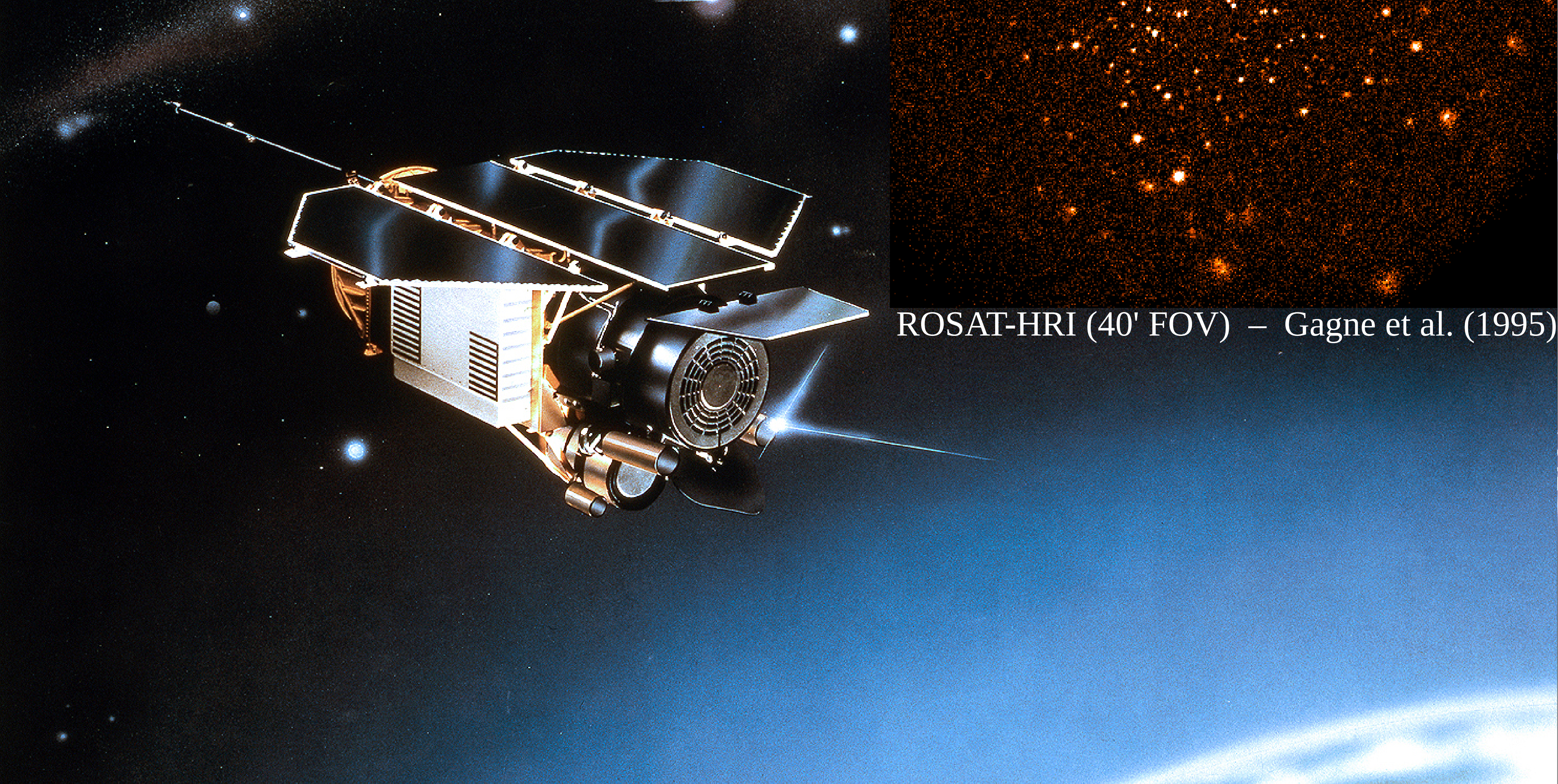
EINSTEIN OBSERVATIONS OF ORION NEBULA

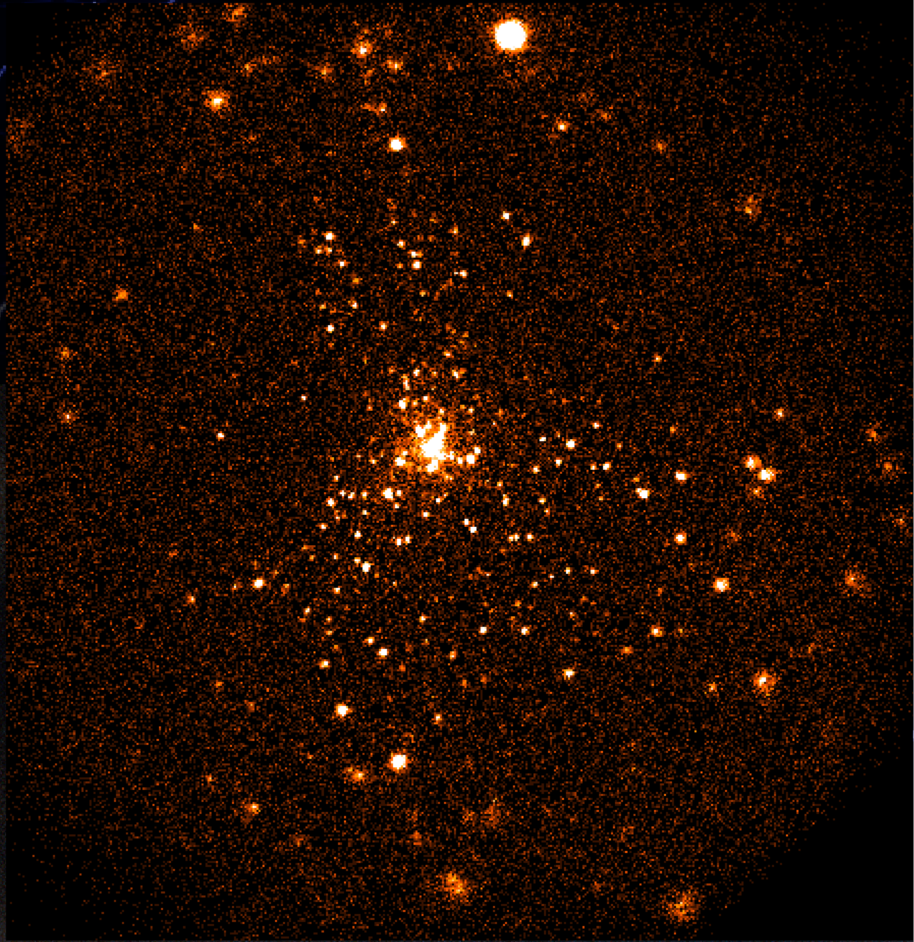


First X-ray "image"

Ku & Chanan (1979)

The ROentgen SATellite ROSAT



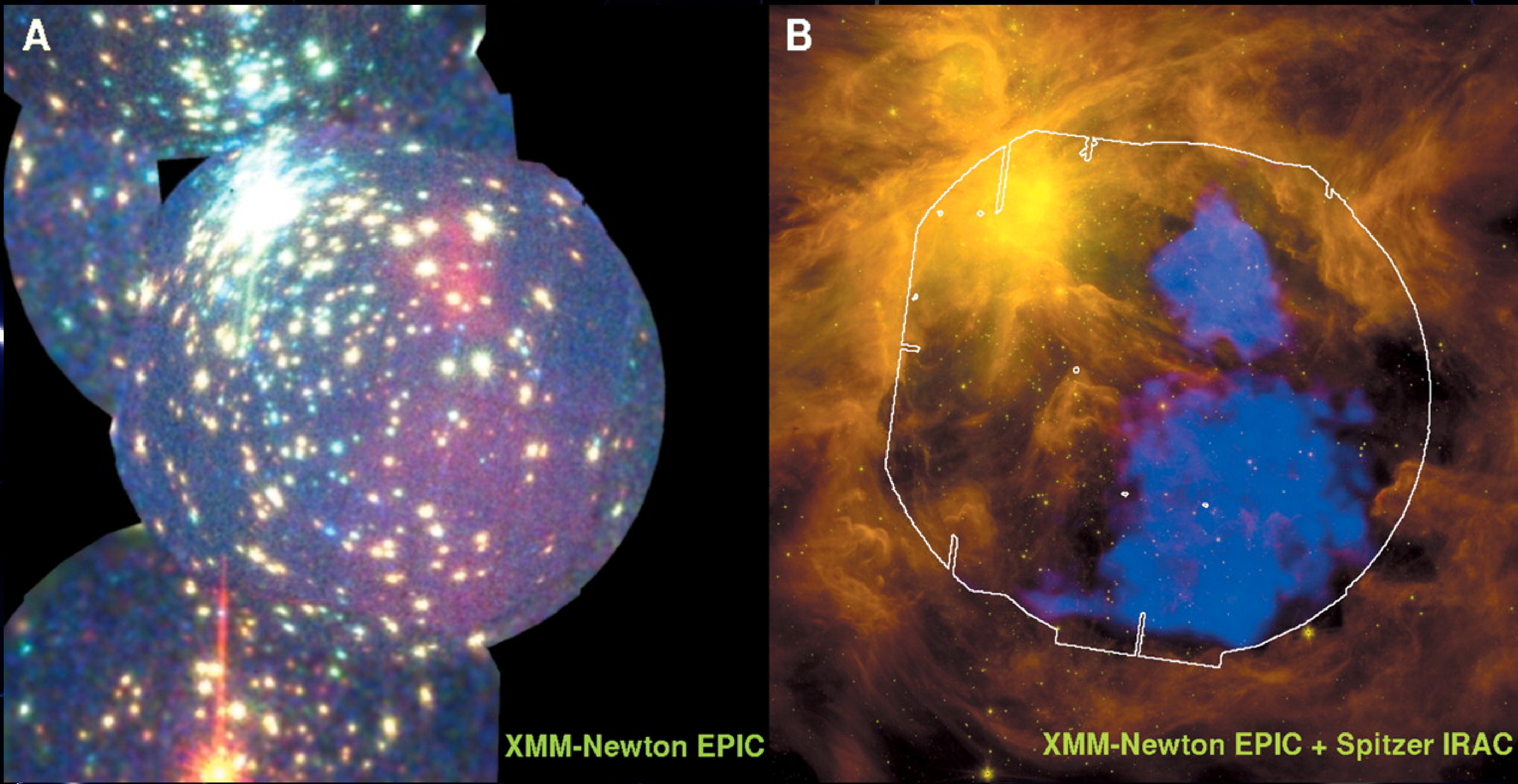


ROSAT-HRI (40' FOV) – Gagne et al. (1995)

The Chandra Orion Ultradeep Project (COUP): a total exposure time of 838 ksec (Feigelson et al. 2005)

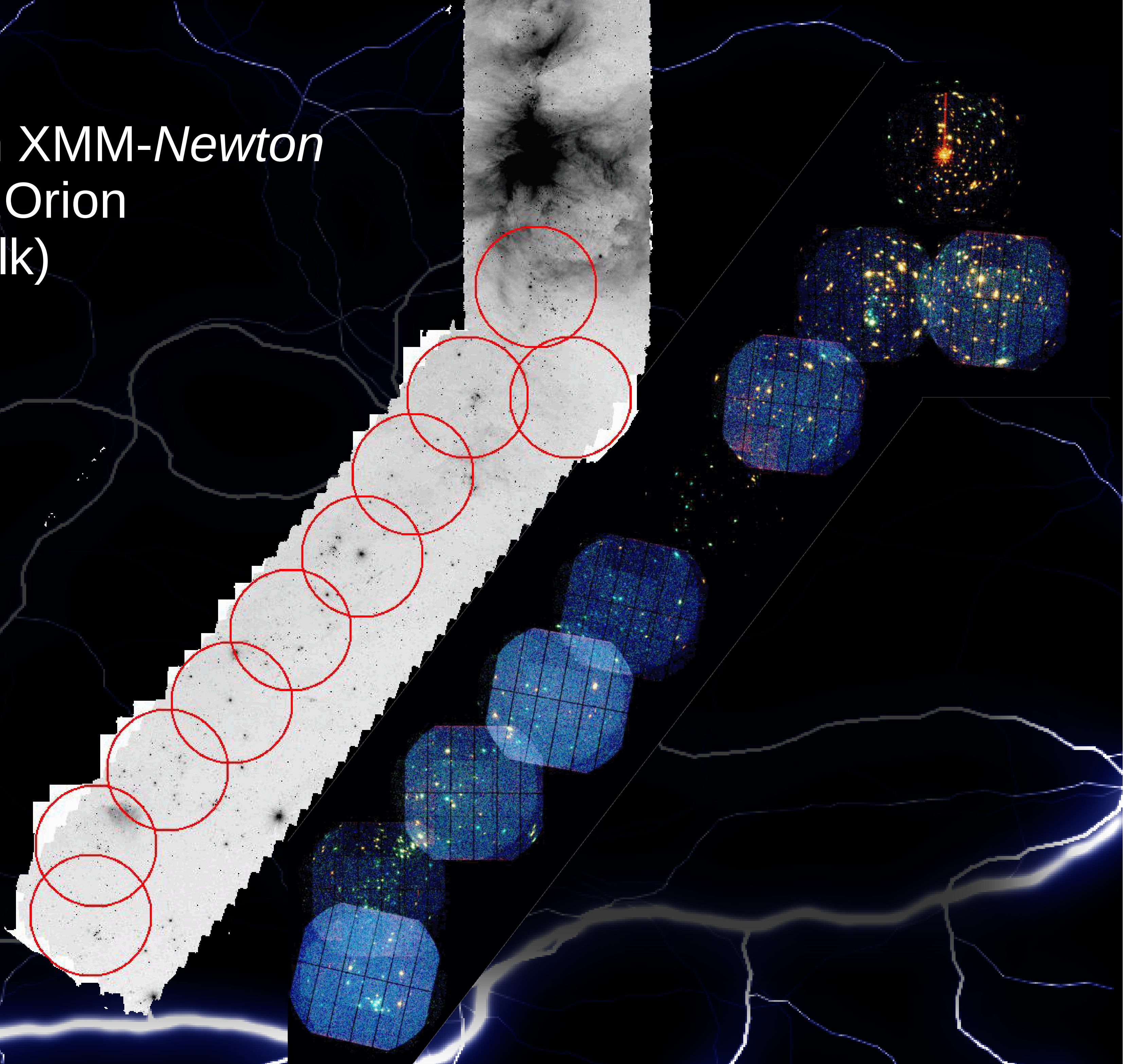
Credit: X-ray: NASA/CXC/Penn State/E.Feigelson & K.Getman et al.; Optical: NASA/ESA/STScI/M. Robberto et al.

Credit:NASA/CXC/Penn State/E.Feigelson & K.Getman et al.



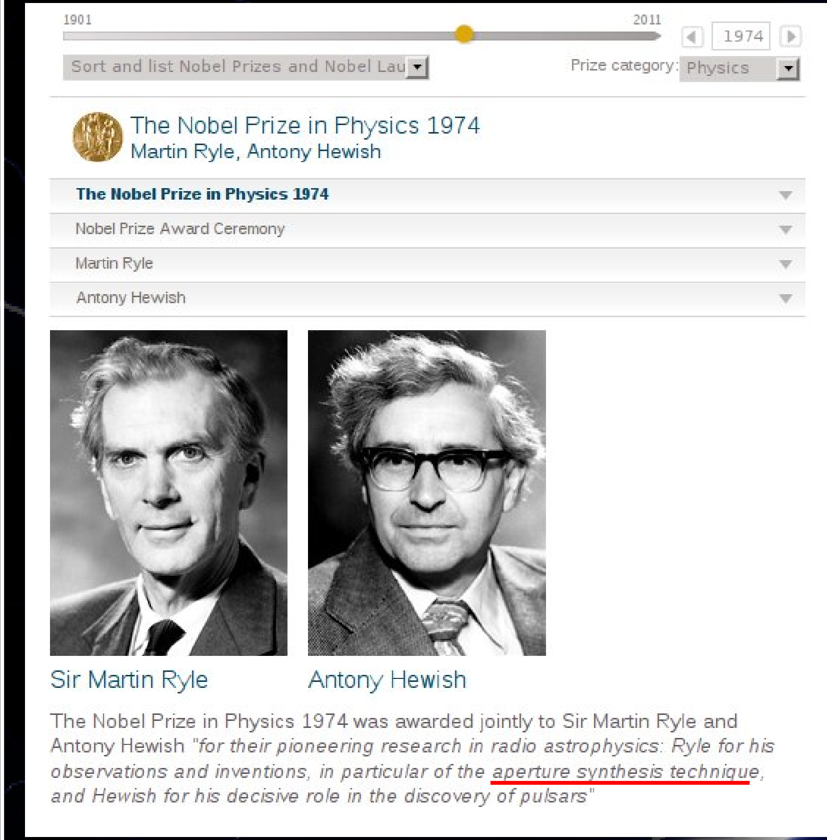
Guedel et al. 2008

SOXS: An XMM-*Newton* Survey of Orion (Scott Wolk)



The Orion Nebula Cluster: the radio view

(The VLA)



DETECTION OF RADIO EMISSION FROM THE BECKLIN-NEUGEBAUER OBJECT

J. M. MORAN,[1] G. GARAY, AND M. J. REID
Harvard-Smithsonian Center for Astrophysics
R. GENZEL
Physics Department, University of California, Berkeley
AND
M. C. H. WRIGHT AND R. L. PLAMBECK
Radio Astronomy Laboratory, University of California, Berkeley
Received 1982 December 10; accepted 1983 April 13

ABSTRACT

We report the detection of radio emission from the Becklin-Neugebauer (BN) object at 15 and 23 GHz with the VLA. The source is smaller than 0″.07 and has a brightness temperature greater than 11,000 K. We did not detect it with the Hat Creek interferometer at 88 GHz to a limit of 70 mJy. The spectral index is ~ 2 between 15 and 23 GHz, suggesting that the emission is optically thick in that range but becomes optically thin above ~ 40 GHz. The radio emission could arise from either a homogeneous H II region of electron density ~ 10^7 cm^{-3} or an ionized stellar wind with a finite recombination radius. In either case, the total mass of hydrogen is ~ 10^{-6} $M_\odot$ and the radius is ~ 3×10^{14} cm. The volume emission measure (~ 10^{60} cm^{-3}) derived for the wind model is consistent with the 4 μm Brα flux density. However, if the radio H II region is homogeneous, the Brα emission must come from a second, denser component of smaller angular size.

Only one other compact continuum radio source was found within 30″ of BN, at a 3 σ flux density limit of 3 mJy at 15 GHz. It has a flux density of 5 mJy and is not coincident with any of the infrared sources in the Orion-KL region. We detected no emission from IRc2.

Maser science in Orion started in parallel...

542 GARAY, MORAN, AND REID 1987

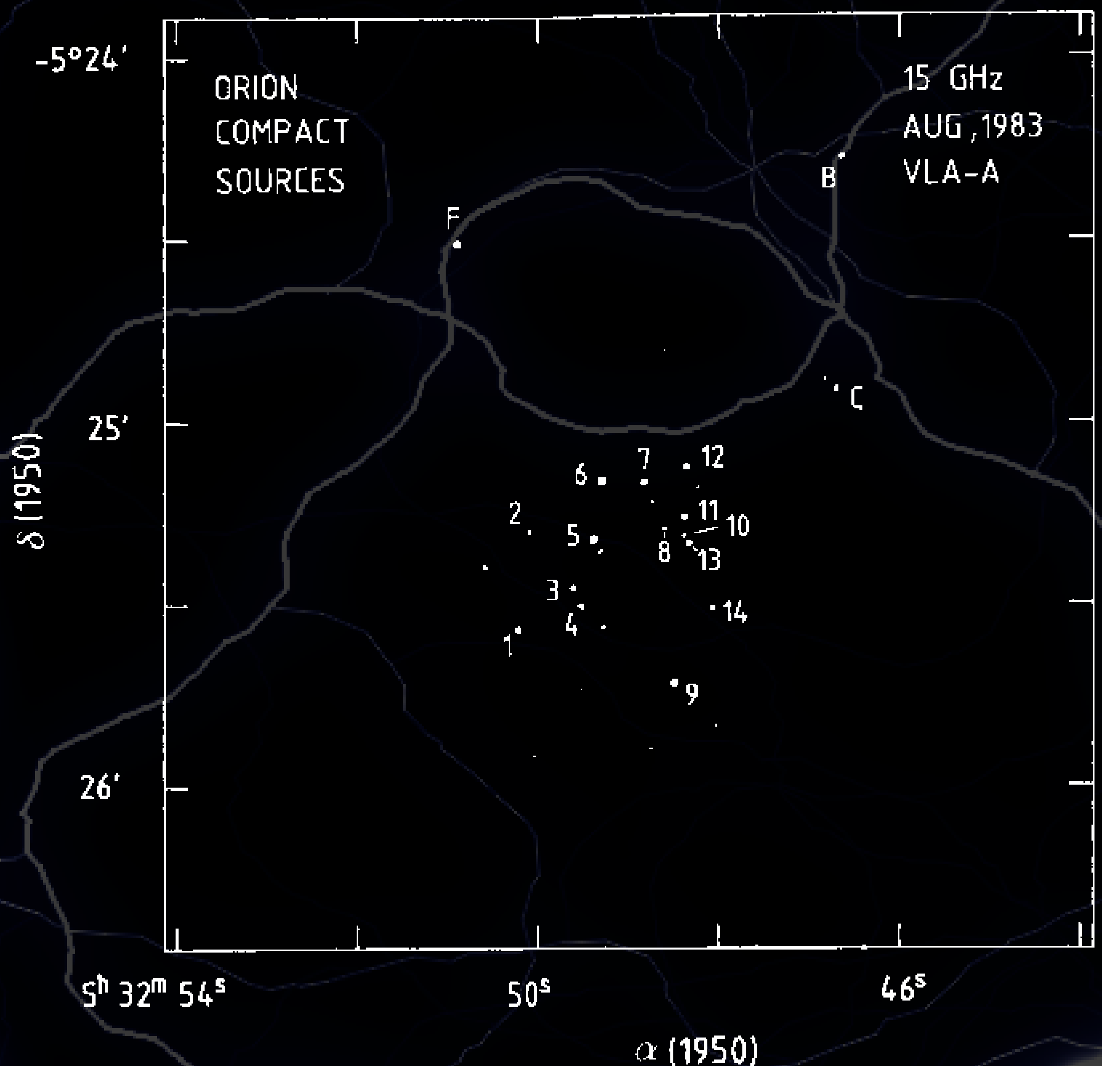


FIG. 4.– Map of the compact radio sources in the Orion Nebula at 15 GHz made with the VLA in the A configuration in 1983 August. Filled circles denote radio sources detected above the limit of 4 mJy per beam area.

Garay et al. (1987) used the VLA at cm wavelengths (and its spatial filtering!) to find

14 radio sources toward the Trapezium (1-14)

7 embedded radio sources in the surroundings (A-G)

With the VLA it became possible to look for counterparts at other wavelengths...
...the radio zoo was born.

See also Churchwell et al. (1987) and Felli et al. (1993a).

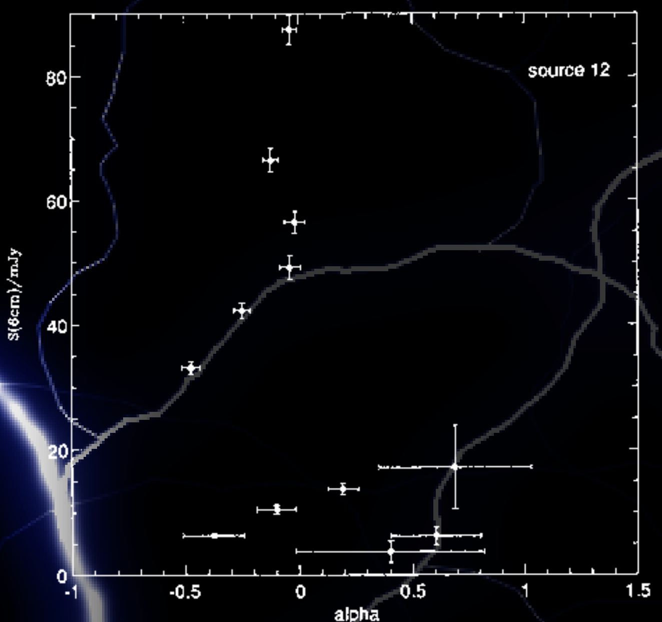


Fig. 6. The spectral index $\alpha(6 - 2$ cm) as a function of integrated flux density at 6 cm for source 12 = θ^1Ori A

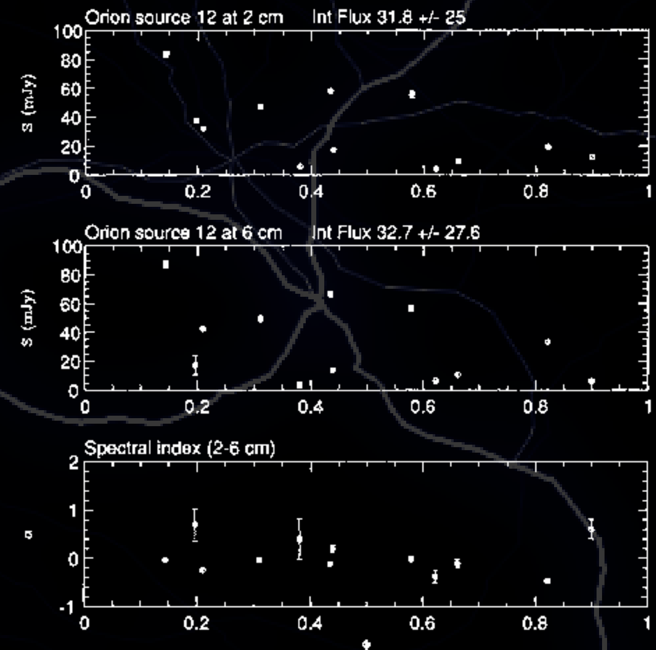


Fig. 7. The radio light curves of source 12 = θ^1Ori A as a function of orbital phase. Top panel 2 cm data, middle panel 6 cm data, bottom panel spectral index

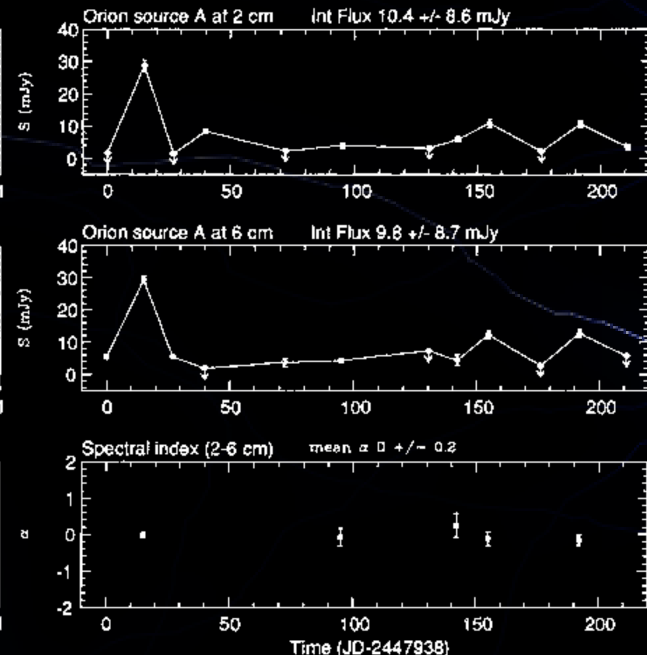


Fig. 29. Same as Fig. 5, for source A

Felli et al. (1993):
1990 Feb 15 – 1990 Sep 14: 13 epochs of VLA two-frequency monitoring of the ONC, to distinguish thermal and non-thermal sources by variability and spectral index

The ORZ

THE ORION RADIO ZOO: PIGS, DEERS AND FOXES

Guido Garay (1987)

European Southern Observatory, Garching b. Munich, FRG
and
Departamento de Astronomía, Universidad de Chile, Santiago, Chile

ABSTRACT. Recent VLA radio observations of a ~ 3'×3' region of the Orion Nebula, centered near the core of the KL nebula, revealing the presence of thirty-five ultracompact radio sources are discussed. Twenty-five of the radio sources are clustered near θ^1C Orionis, the most luminous star of the Trapezium cluster, and have optical counterparts. Most of these objects are probably neutral condensations surrounded by ionized envelopes that are excited by θ^1C. The partially ionized globules (PIGS) have (FWHP) sizes of $\sim 2 \times 10^{15}$ cm and if their electron densities have the form $n_e \propto r^{-2}$, then a typical neutral condensation radius is $\sim 6 \times 10^{14}$ cm and the electron density just beyond that radius is $\sim 10^6$ cm^{-3}. Four radio sources, the DEERS, are projected toward the dense core of the Orion molecular cloud and are invisible optically. Two of these are coincident with luminous infrared objects in the Orion-KL region. The DEERS are thus likely to be embedded in the molecular cloud and associated with young, recently formed luminous stars. Hence their acronym as Deeply Embedded Energetic Radio Sources. Three radio sources, the FOXES, are near the dark bay that indents the Orion Nebula. The FOXES exhibit variability in their radio emission and are associated with variable X-ray and optical objects. Hence their acronym as Fluctuating Optical and X-ray Emitting Sources. They probably are pre-main sequence (T Tauri) stars. A suggestion for the sequential formation of the Orion radio zoo species is made, as is for the triggering mechanism.

Key words: INFRARED-SOURCES — NEBULAE-ORION — RADIO SOURCES-IDENTIFICATION

PIGS
DEERS
FOXES

Externally Ionized (accretion) Disks in the Environs of Radiation Sources (EIDERS,or … proplyds)

Finally, the results of this work amply confirm the existence of the "Orion Radio Zoo" first recognized and elegantly discussed by Garay (1987). In the course of this study, we have identified EIDERS as a potential additional inhabitant of the zoo. An important question is whether more inhabitants than PIGS, DEERS, EIDERS, and FOXES are present, and if so, can we observationally distinguish between them? This work has shown that multi-epoch, multi-frequency observations must be elements in the arsenal employed to understand the nature of the currently identified inhabitants of this young star formation region.

Felli et al. (1993b)

BIODIVERSITY LOSS IN THE ORION RADIO ZOO?

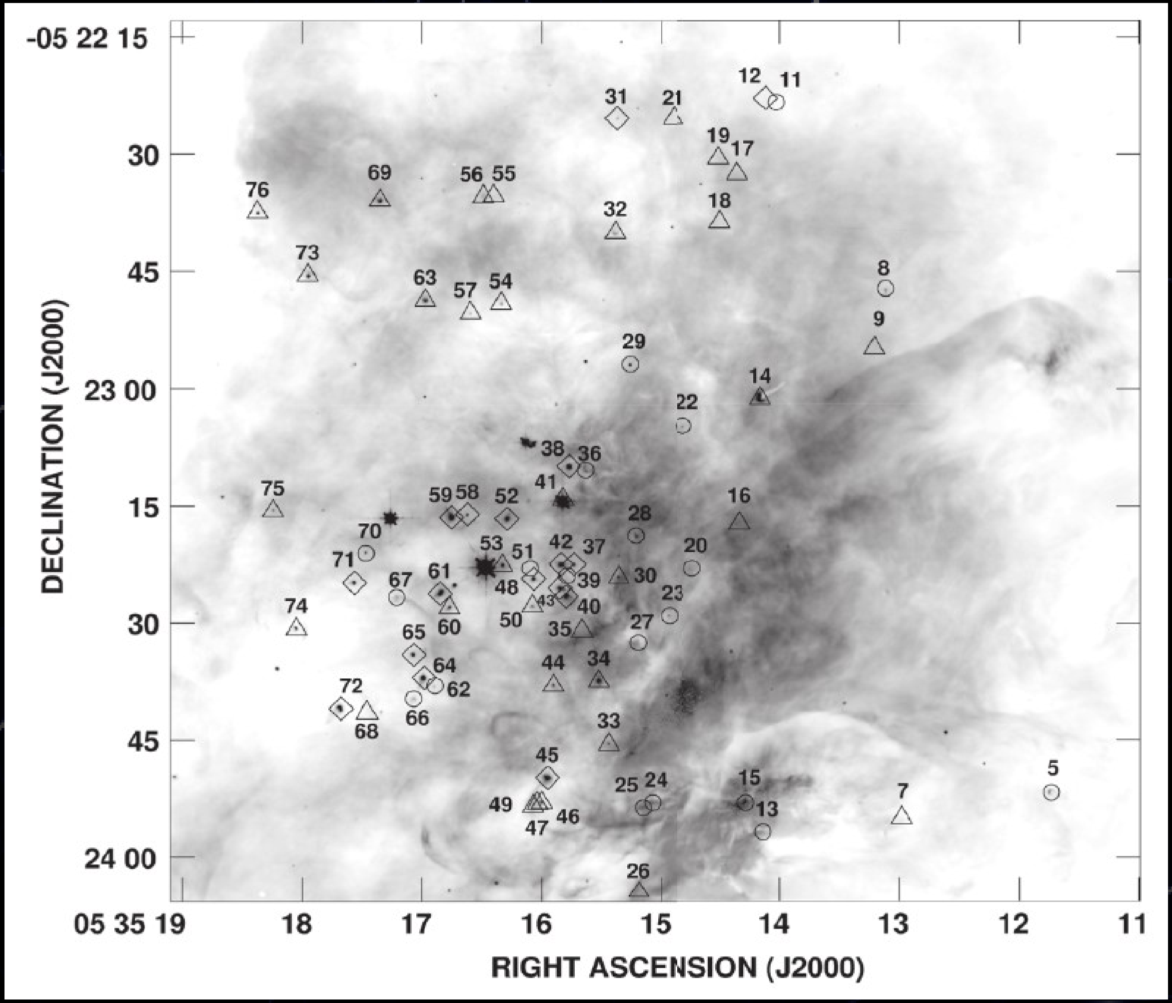
W. J. Henney, Ma. T. García-Díaz, and S. E. Kurtz (2001)

Instituto de Astronomía, UNAM

ABSTRACT

We re examine radio observations of compact sources in the core of the Orion nebula and find that 70% of the sources correspond to known proplyds. For all of these sources, including many that have been previously classified as variable and non thermal, the radio flux between 1.5 and 86 Ghz is fully accounted for by thermal free free emission from the photoevaporation flow. We therefore suggest that many of the proposed Orion FOXES are in fact EIDERS, and that their apparent variability reflects observational difficulties in detecting the lower surface brightness portions of the proplyds. The PIGs turn out to be extinct in Orion, and the hybrid creatures that we dub PANTHERS (Proplyds Associated with Non THErmal Radio Sources) remain elusive.

Key Words: **H II REGIONS — INTERFEROMETRY — ISM: INDIVIDUAL (M42) — STARS: CIRCUMSTELLAR MATTER**

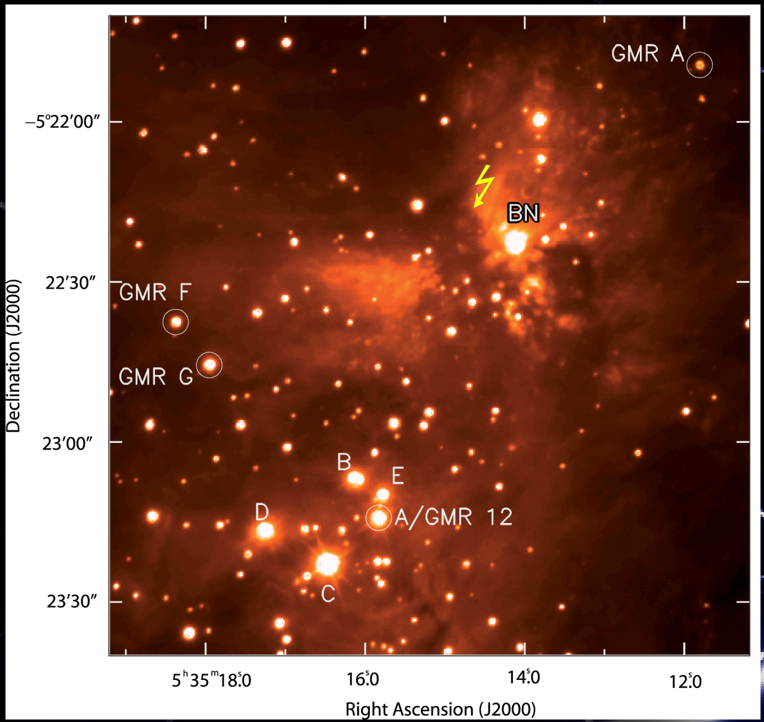


Zapata et al. (2004): four deep epochs (1994-1997) of 8.5 GHz VLA observations yield 77 sources … so far the last word. Sources are superimposed on H image from O'Dell & Wong (1996)

Continuum VLBI toward the ONC

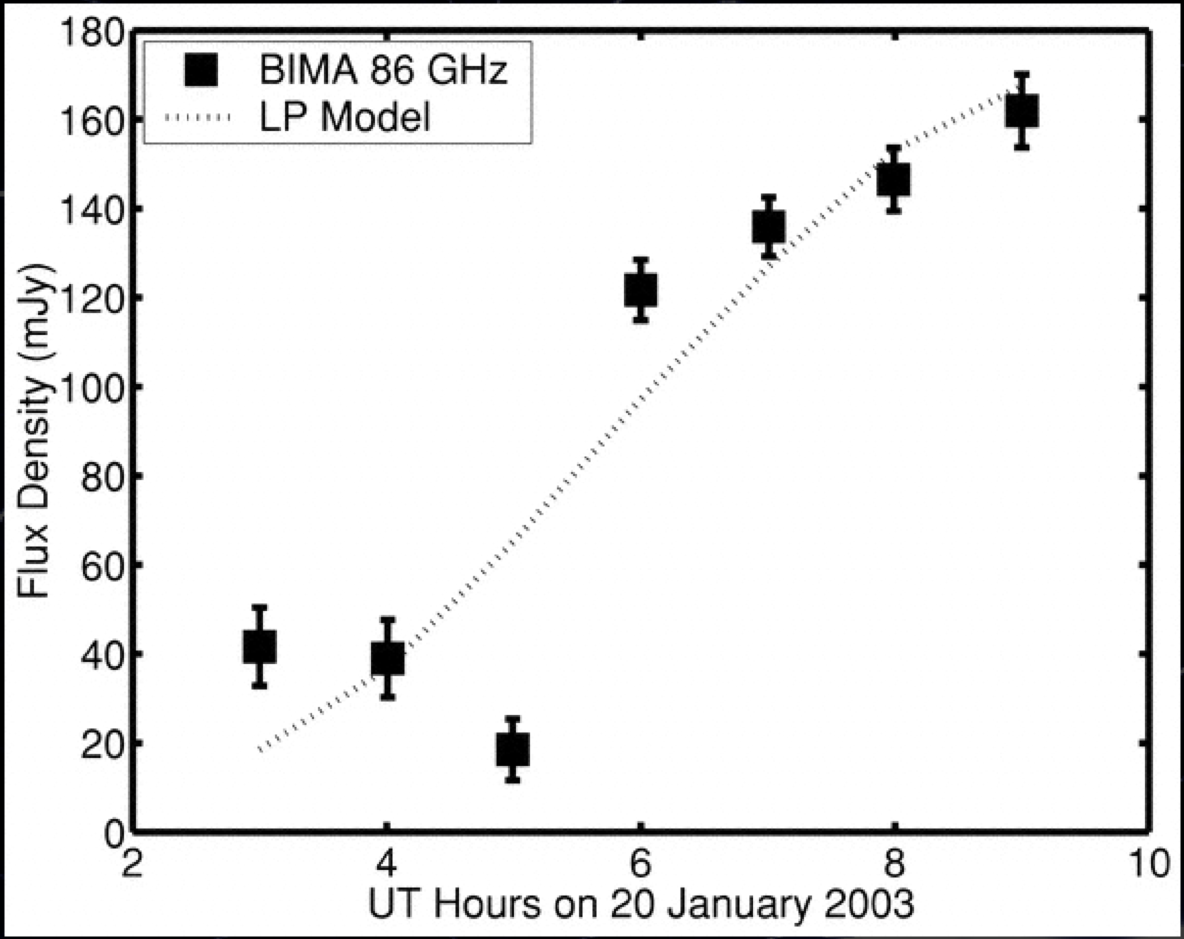
- Non-thermal emission from hot(?) stars: Θ^1 Ori A (Felli, Massi, et al. 1989, 1991, cf. Petr-Gotzens & Massi 2008)
- Non-thermal emission from YSOs: Menten, Reid, Forbrich & Brunthaler (2007)

→ d = 414±7 pc
(cf. Sandstrom et al. 2007)



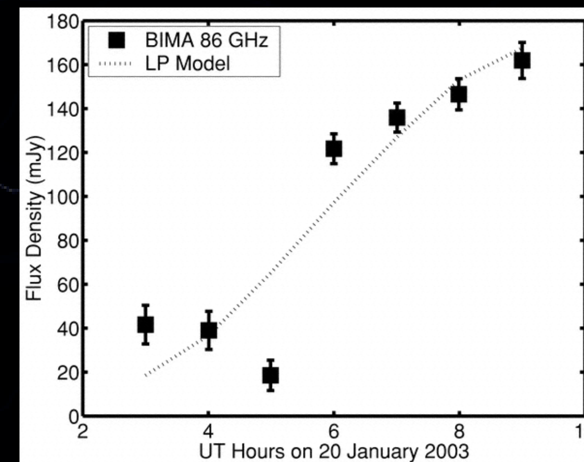
VLT K-band, Mark McCaughrean

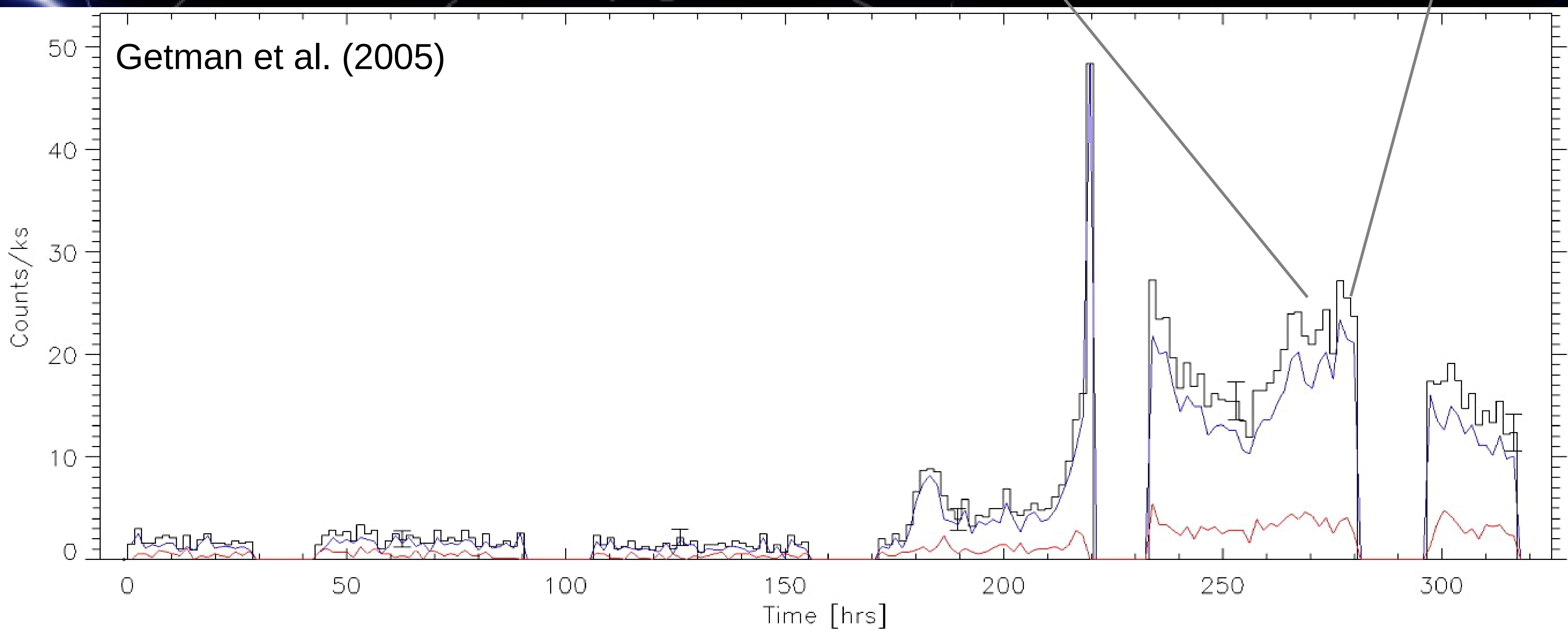
YSOs as transient radio sources



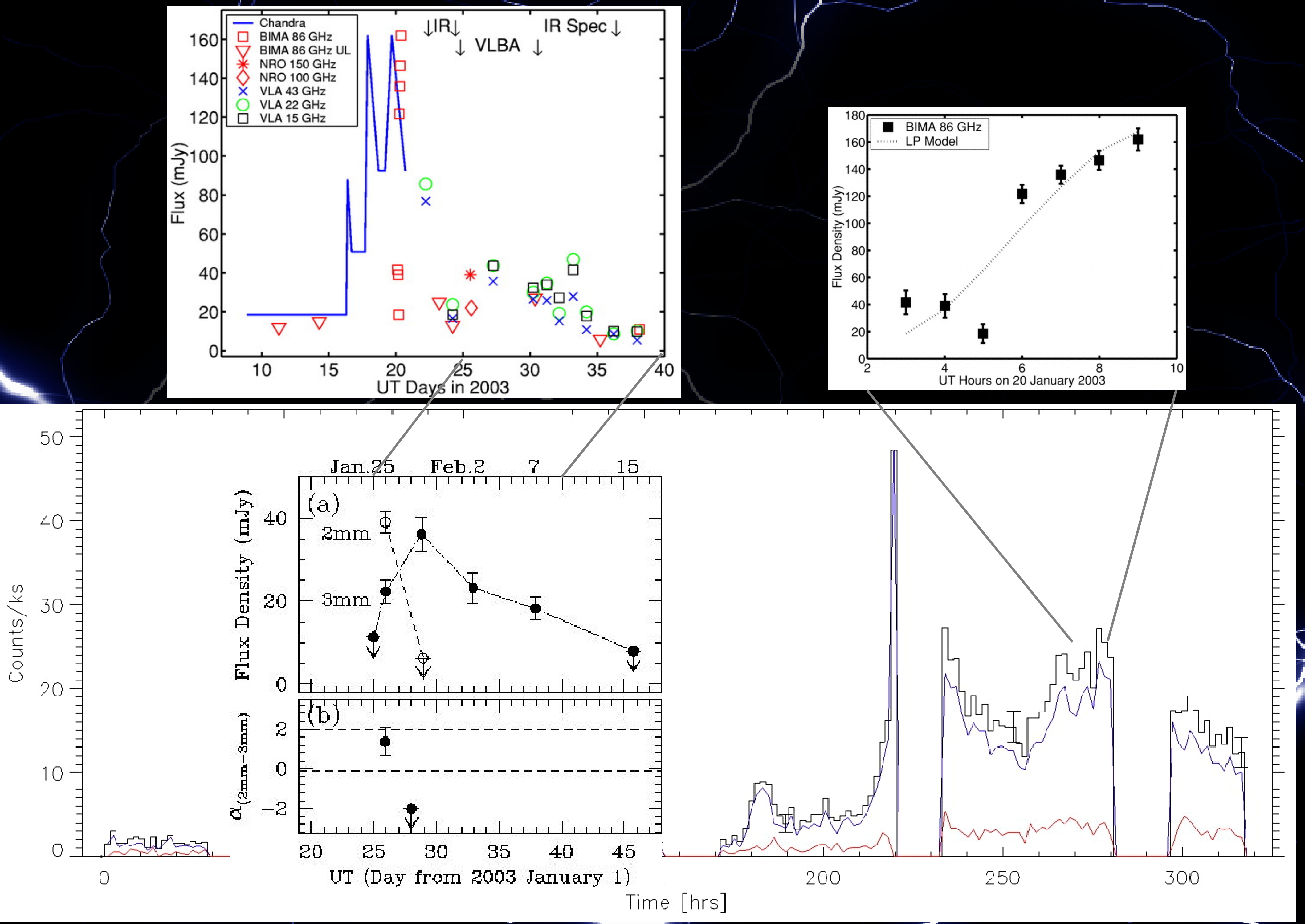
GMR A (Bower et al. (2003)

GMR A (Bower et al. 2003)

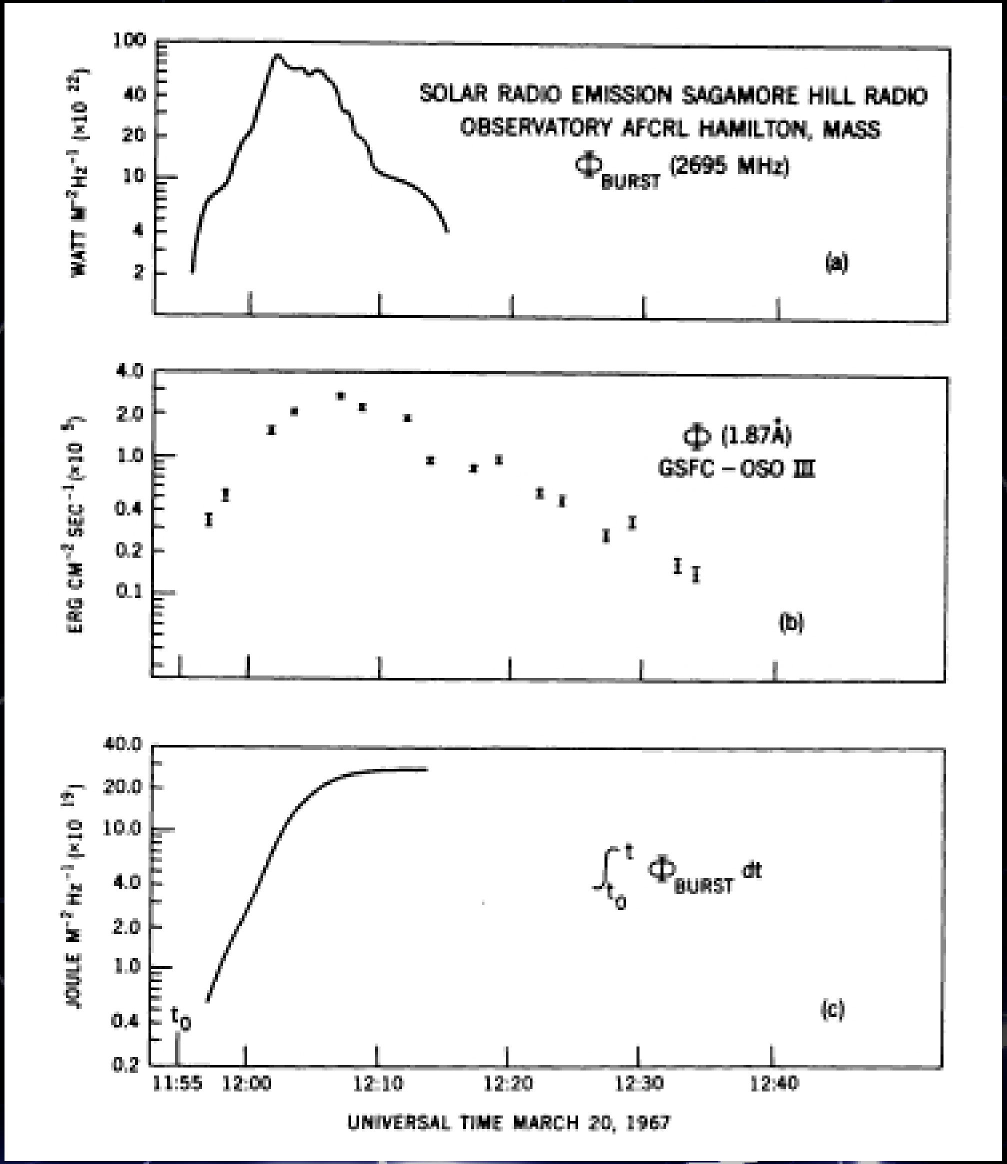




GMR A (Bowser et al. 2003, Furuya et al. 2003)



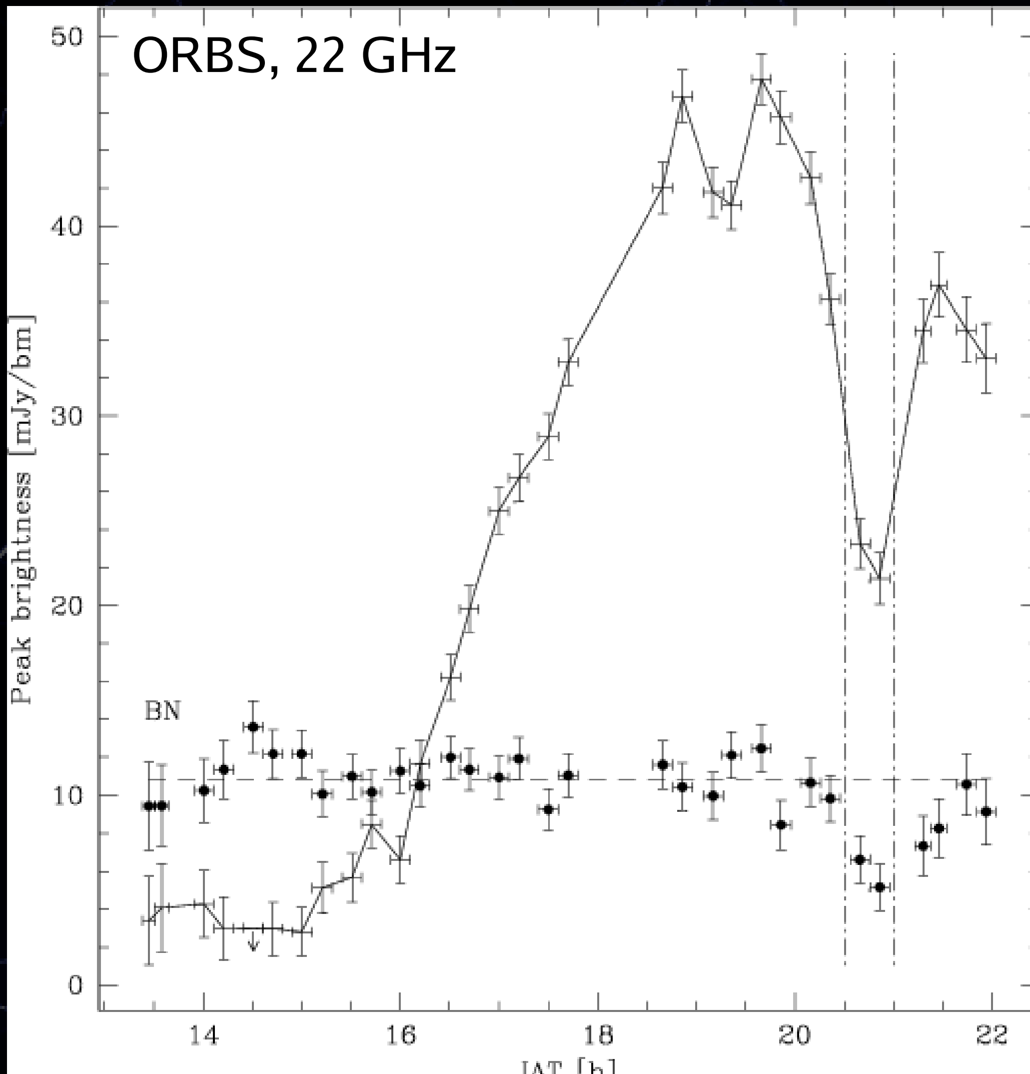
The solar paradigm II



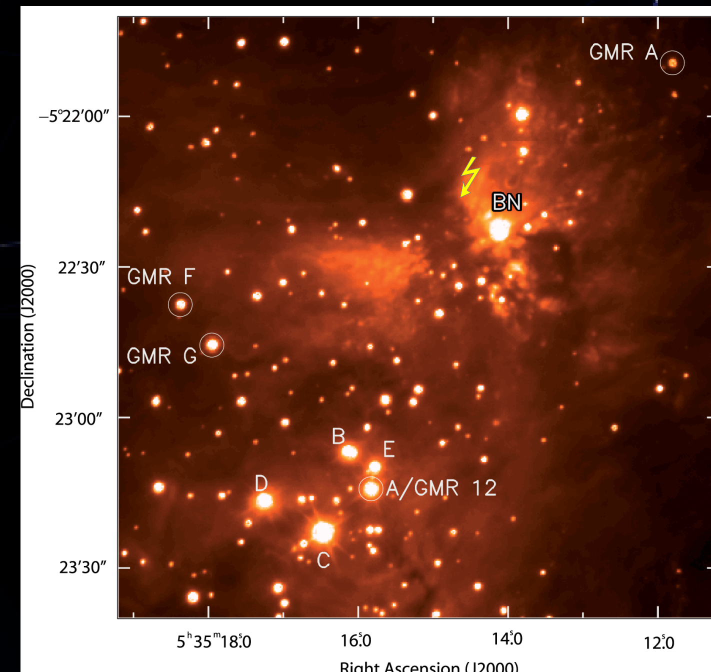
$$L_R(t) \propto \frac{d}{dt} L_X(t)$$

(Neupert 1968)

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

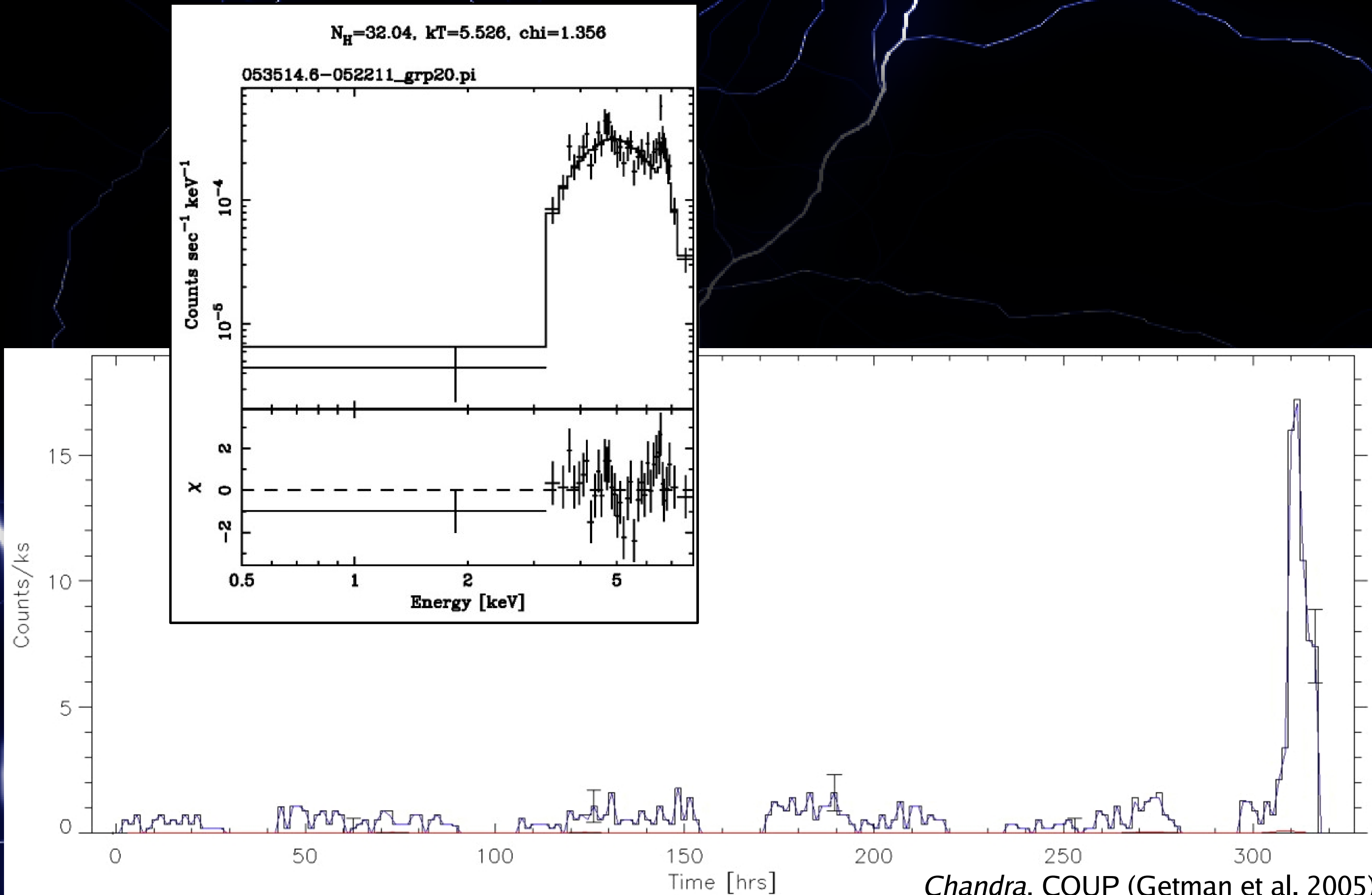


Forbrich, Menten, & Reid (2008)



A_V ~ 160 mag, no infrared counterpart

(from X-rays; spectrum shows fluorescent iron line emission)



Chandra, COUP (Getman et al. 2005)

A_V ~ 160 mag, no infrared counterpart

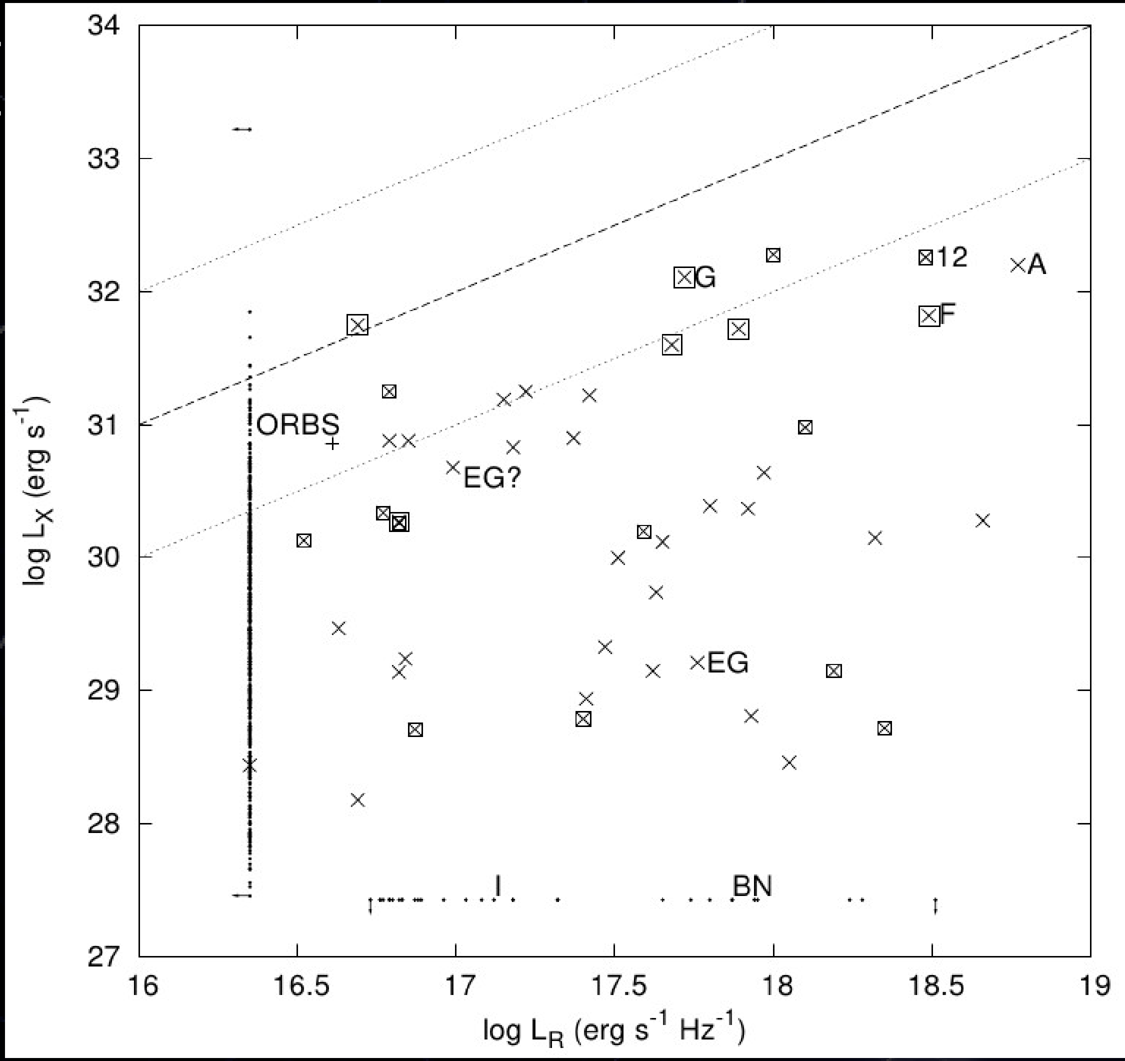
(from X-rays; spectrum shows fluorescent iron line emission)

Simultaneous X-ray/radio observations of YSOs

- V773 Tau, a WTTS multiple (near-simultaneous in Feigelson et al. 1994), see also Guenther et al. (2000) with a short span of simultaneous data
- GMR A (Bower et al. 2003), a WTTS, with a *flare!*
- ρ Oph (Gagné et al. 2004), six TTS
- *Coronet* cluster (Forbrich et al. 2007), six class I, one CTTS, one HAeBe
- LkHα 101 (Osten & Wolk 2009), six(+1?) TTS
- NGC 1333, IC 348 (Forbrich et al. 2011), few simultaneous X-ray/radio detections

The latest on the X-ray-radio correlation in the ONC

Forb rich & Wolk, *in prep.*



60% of the radio sources have X-ray counterparts

7% of the X-ray sources have radio counterparts

Comparison clearly limited by the radio data.

VLA data from Zapata et al. (2004),
X-ray data from the COUP (Getman et al. 2005)

Outlook

• The advent of the EVLA a.k.a. JVLA places stellar radio astronomy where stellar X-ray astronomy was in 1999, at the time of the launch of *Chandra* and XMM-*Newton:*

• Higher S/N observations will allow variability studies and "imaging spectroscopy/polarimetry".

This Fall

Forbrich, Wolk, Menten, & Osten:
Multi-epoch simultaneous JVLA/*Chandra* observations of the ONC.