MICROARCSECOND X-RAY IMAGING OF STARS

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"Why has not man a microscopic eye?
For this plain reason, man is not a fly."
Alexander Pope 1688–1744

"Ad astera per aspera."
To the stars through difficulties.

SCIENCE OBJECTIVES OF ULTRAHIGH RESOLUTION X-RAY IMAGING OF STARS

Coronal Structure of late-type stars and binary systems: How extended are these coronae? Are coronae usually solar-like consisting of groups of magnetic loops filled with hot X-ray emitting plasma surrounded by low density low emissivity regions, or do the more active stars have very different structures? For example, is most of the X-ray emission from active stars located near the equator or the magnetic poles?

Location of flaring plasmas: Do flares occur close to the stellar surface or several radii above the surface? How fast do flares move? Do flares occur near regions of strong magnetic fields? Are flares very compact or do they fill loops with dimensions of a stellar radius or larger? Are x-ray and radio flares cospatial?

Evidence for magnetic fields in coronae: Do coronae show loop-like structures indicative of magnetic fields? Do active regions overlie dark starspots (which presumably have strong magnetic fields)?

Location of hot plasma in close binaries: One popular model places the hottest plasma close to each star, while a model based on eclipse data places the hottest plasma in an extended region well above the stellar surface. Is either model valid?

Do magnetic fields of binary stars interact? The location of flares between binary stars may help to answer this question.

Location of hot plasma in PMS stars: Is the hot plasma located around the PMS star, in the accretion disk, or in an intermediate region where the magnetic fields of the star and the accretion disk interact?

Location of hot plasma in hot star winds: Is the hot plasma produced by shocks deep in the wind or far from the star? What is the structure of these shocks?

Colliding stellar winds: Binary systems consisting of two hot stars (O or WR type) with strong winds are luminous X-ray sources. Is the X-ray emission primarily from the region between the stars where the winds interact? Shat is the structure (shape, thickness, extent) of the X-ray emitting region?

Location of hot plasma in X-ray binaries: Examples include Algols, CVs, AM Her systems, LMXBs, HMXBs, etc.

RECENT STELLAR CORONAL IMAGING STUDIES

(a) X-ray Eclipse Mapping (Poorman's X-ray interferometry)

Popular Targets: AR Lac and TY Pyx

Parameter	AR Lac	TY Pyx
Distance (pc)	47	55
Period (days)	1.983	3.2
Sp. Type (1)	G2 IV	G5 IV
Sp. Type (2)	K0 IV	G5 IV
Separation ($R_\odot$)	9.22	12.25
R_1 ($R_\odot$)	1.8	1.59
R_2($R_\odot$)	3.1	1.68
θ_D^1 (mas)	0.36	0.27
θ_D^2 (mas)	0.61	0.28
Max. Radial Vel. Separation	232	174

- Einstein IPC+MPC observation of AR Lac analyzed by Walter, Gibson and Basri (ApJ 267, 665 (1983)). Evidence for compact structures (scale heights $\sim 0.02R_\star$) and extended emission (scale heights $\sim R_\star$) around the K 0 IV star.

- July 1984 Exosat observations of AR Lac analyzed by White et al (ApJ 350, 776 (1990)) with a maximum entropy reconstruction method. An eclipse seen at low energy but not at 1–6 keV.

- Exosat observations of TY Pyx analyzed by Culhane et al (MNRAS 243, 424 (1990)). Eclipses seen at low energy by not in the medium energy channel. Emitting structures appear to connect the two stars. Reanalysis by Siarkowski et al (ApJ 473, 470 (1996)) shows a loop-like structure interconnecting the stars containing 40% of the total emission.

- July 1984 ROSAT observations of AR Lac (Ottmann et al (ApJ 413, 710 (1993)) show primary eclipse at all energies. Their model shows a compact feature on the G2 IV star ($\sim 0.03R_\odot$) and and extended structure aroung the K0 IV star ($\sim 1-2R_\odot$).

- December 1990 ROSAT observations of AR Lac analyzed by Pres et al (MNRAS 275, 43 (1995)) shows a few compact structures (33%) near the surfaces of both stars and extended emission (44%) pervading the whole binary system.

- June 1993 ASCA observations of AR Lac analyzed by White et al (PASJ 46, L97 (1994)) show primary and secondary eclipses at all energies. Reanalysis by Siarkowski et al (1996) shows compact structures, emission between the stars, and an extended halo.
- Question: Are we seeing major changes in the emitting structures, or are we fooled by inadequate resolution and artifacts introduced by the inversion techniques?

(b) Radio VLBI/VLBA

An example: VLBA/VLA map of UV Cet B (dM5.5e) at 3.6 cm by Benz, Güdel, and Conway (A+A 331, 596 (1998)). With a 1.8 x 0.7 mas beam they see 2 sources (one resolved at 0.59 mas $= 1.2 R_\star$) and the other possibly unresolved. Separation of the two components is 4–5 $R_\star$. They are aligned along the binary orbit and thus probably along the stellar rotation axis. This suggests large loops in the corona with magnetic field of 20–130 G. For the resolved component $T_B = 3 \times 10^8$ K.

(c) Doppler Imaging in UV and Optical

An example: Observations of the Pleiades-age star AB Dor (K0 V) by Collier Cameron and Robinson (MNRAS 236, 57 and MNRAS 238, 657 (1989)). Dynamic spectra of the Hα line show absorption features that move from the red to the blue wing during about 10% of an orbital period. These are interpreted as stellar prominences extending out to 3–9 $R_\star$ and corotating with the star. This provides evidence for large magnetic structures in the coronae of active stars.

TEST CASES: IS MICROARCSECOND IMAGING PHOTON STARVED?

The angular diameter (in milliarcseconds) of a star at d parsecs:

$$\theta_D = 9.3 \frac{(R/R_\odot)}{d(pc)} mas.$$

The S/N per resolution element for a star with an apparent x-ray flux of f_X^{tot} (ph/cm^2/s) observed with an instrument with an angular resolution of θ_{instr} (mas):

$$(S/N)^2 = \frac{A_{eff}(cm^2)t_{obs}(s)}{b} f_X^{tot}(ph/cm^2/s)(\theta_{instr}/\theta_D)^2,$$

where b is the fraction of pixels filled with uniform X-ray emission. Assume all photons have hν = 1 keV, no X-ray background, and

$$\frac{A_{eff}(cm^2)t_{obs}(s)}{b} = \frac{10^2 \times 10^4}{0.1} = 10^7.$$

then

$$(S/N)^2 = 10^7 f_X^{tot}(ph/cm^2/s)(\theta_{instr}/\theta_D)^2.$$

Target	Type	$R/R_\odot$	d(pc)	θ_D (mas)	log L_X	f_X^{tot} (ph/cm^2/s)
Prox Cen	flare star	0.16	1.3	1.14	27.2	0.0048
UV Cet	flare star	0.14	2.7	0.48	27.3	0.00144
AU Mic	flare star	0.57	9.4	0.56	29.8	0.038
α Cen A	G2 V	1.24	1.35	8.5	27.3	0.0067
AB Dor	young star	0.8	15.0	0.50	30.2	0.037
AR Lac	RS CVn binary	1.8/3.1	47	0.36/0.61	31.0	0.024
Capella	binary	8.7/12.6	13.0	6.2/9.0	30.6	0.12
TW Hya	PMS star	3	56	0.50	30.0	0.0016
SU Aur	PMS star	2.9	140	0.19	30.8	0.0015
θ^1 Ori C	O7 star	10	440	0.21	32.4	0.0063
θ^1 Ori C	wind	100	440	2.1	32.4	0.0063
WR147	WR + O	20	630	0.30	32.6	0.0052

Target	θ_D (mas)	f_X^{tot} (ph/cm^2/s)	S/N for θ_{instr} (mas)			Num. res. elements for θ_{instr} (mas)		
			0.1	0.01	0.001	0.1	0.01	0.001
Prox Cen	1.14	0.0048	19	1.9	0.19	130	1.3(4)	1.3(6)
UV Cet	0.48	0.00144	25	2.5	0.25	23	2.3(3)	2.3(5)
AU Mic	0.56	0.038	110	11	1.1	31	3.1(3)	3.1(5)
α Cen A	8.5	0.0067	3	0.3	0.03	7.2(3)	7.2(5)	7.2(7)
AB Dor	0.50	0.037	122	12	1.2	25	2.5(3)	2.5(5)
AR Lac	0.36	0.024	136	14	1.4	37	3.7(3)	3.7(5)
Capella	6.2	0.12	18	1.8	0.18	3.8(3)	3.8(5)	3.8(7)
TW Hya	0.50	0.0016	25	2.5	0.25	25	2.5(4)	2.5(6)
SU Aur	0.19	0.0015	63	6.3	0.6	3.6	3.6(3)	3.6(5)
θ^1 Ori C	0.21	0.0063	120	12	1.2	4.4	4.4(3)	4.4(5)
θ^1 Ori C	2.1	0.0063	12	1.2	0.1	440	4.4(4)	4.4(6)
WR147	0.30	0.0052	76	7.6	0.76	9	9(3)	9(5)

CONCLUSIONS

- Nearby members of many classes of stars should be successfully imaged by an x-ray interferometer with θ_{instr} in the range 0.1 mas and $A_{eff} = 100$ cm^2 in 10,000 seconds. With 20–4000 resolution elements across the stellar disk, one can infer the location and size of the bright coronal features. Since coronae are likely extended, the images will determine the off-limb scales of the bright emission features.

- When these stars flare, they can be imaged with shorter exposures and time sequences of such images should show where and how the flaring plasma evolves with time. This is exciting science.

- There are important scientific questions that can be answered at all angular resolutions better than 1 mas. For example, the TRACE image of the Sun can be thought of as an image of a sunlike star located at 10 pc and viewed with about 1 μarcsecond resolution. Smearing the image to 10 or even 100 μarcsecond resolution contains useful new information. Even 1 μarcsecond resolution will provide important information on the location of the X-ray emission in binary systems and in the extended coronae around nearby stars.

- At resolutions of $< 1\mu$as, the coronae of nearby stars will likely be too faint for good imaging. MAXIM Pathfinder rather than MAXIM is the ideal instrument for stellar X-ray imaging.

- Stellar targets provide useful engineering targets along the journey to μarcsecond x-ray imaging and beyond.

- Unexpected discoveries are very likely as ultrahigh resolution imaging at x-ray wavelengths is an unexplored region of parameter space. Just as planetary systems around other stars are very different from the solar system, stellar coronae may be very different from the solar corona.