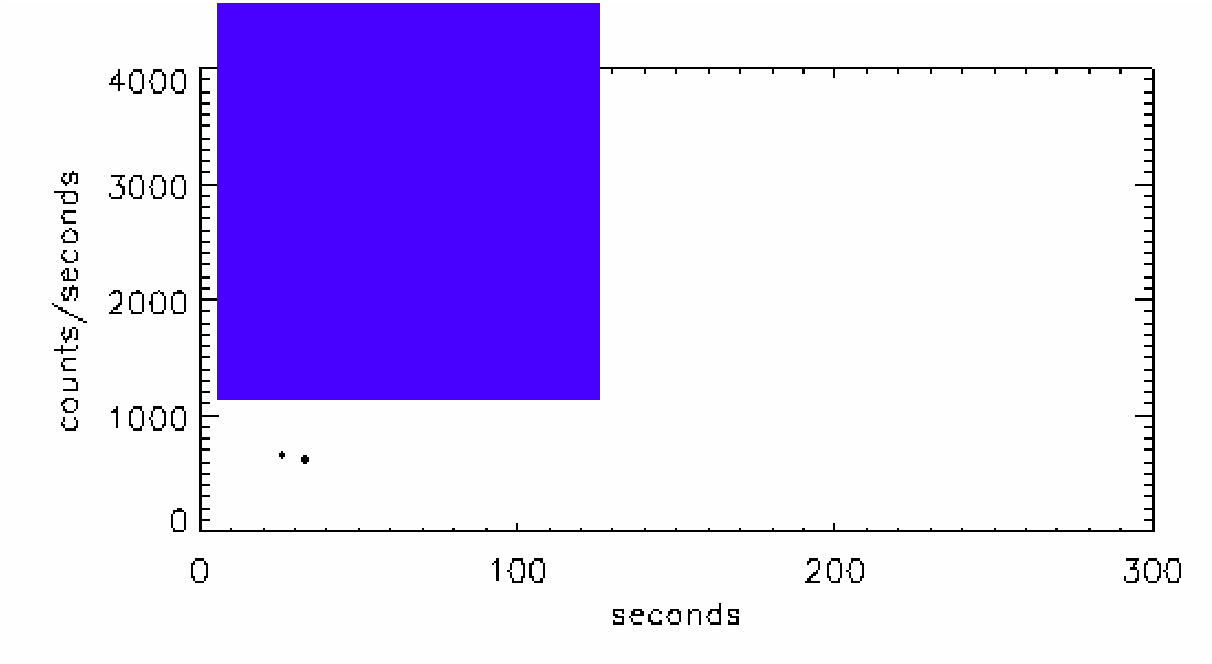
Stellar Transients: Introduction



From IBAS web site

- Definitions
- General overview of transients
- Observational strategies

Units

- **(Photon) energy**: 1 keV = 1.6×10^{-16} J; 1 erg = 10^{-7} J ; 1 keV ⇔ 12.4 Å ($E = h \times c / \lambda$; γ-rays @ > 100 keV; X-rays @ 0.1-100 keV; UV @ 0.003-0.1 keV; optical @ 0.001-0.003 keV)
- **Temperature**: 1 keV => $T = 1.1 \times 10^{7}$ K ($E = kT$)
- **Energy flux**: 1 Crab unit = 2×10^{-8} erg s^{-1} cm^{-2} = 2×10^{-11} W m^{-2} (in 2-10 keV);
- **Flux density**: erg s^{-1} cm^{-2} keV^{-1}; 1 μJy = 10^{-32} W m^{-2} Hz^{-1} = 2.4×10^{-12} erg cm^{-2} s^{-1} keV^{-1}
- **Fluence**: erg cm^{-2} (energy output without distance correction)
- **(Solid) angles**: 1 radian = 57.3 degrees; 1 arcmin (') = 1/60 deg; 1 arcsec (") = 1/3600 deg; 4π steradian = whole sky = 41,253 square degrees
- **Time**: Julian day number (JD) = # days since Jan 1, 4713 BC, Greenwich noon. Modified Julian Day (MJD) = JD - 2,400,000.5 (ie, since Nov 17, 1858 AD, midnight); Truncated Julian Day (TJD) = JD - 2,440,000.5 (ie, since May 24, 1968 AD, midnight). Now (April 22, 2008, afternoon) is JD 2 454 579, MJD 54 578, TJD 14 579..

Definition of (stellar) transient

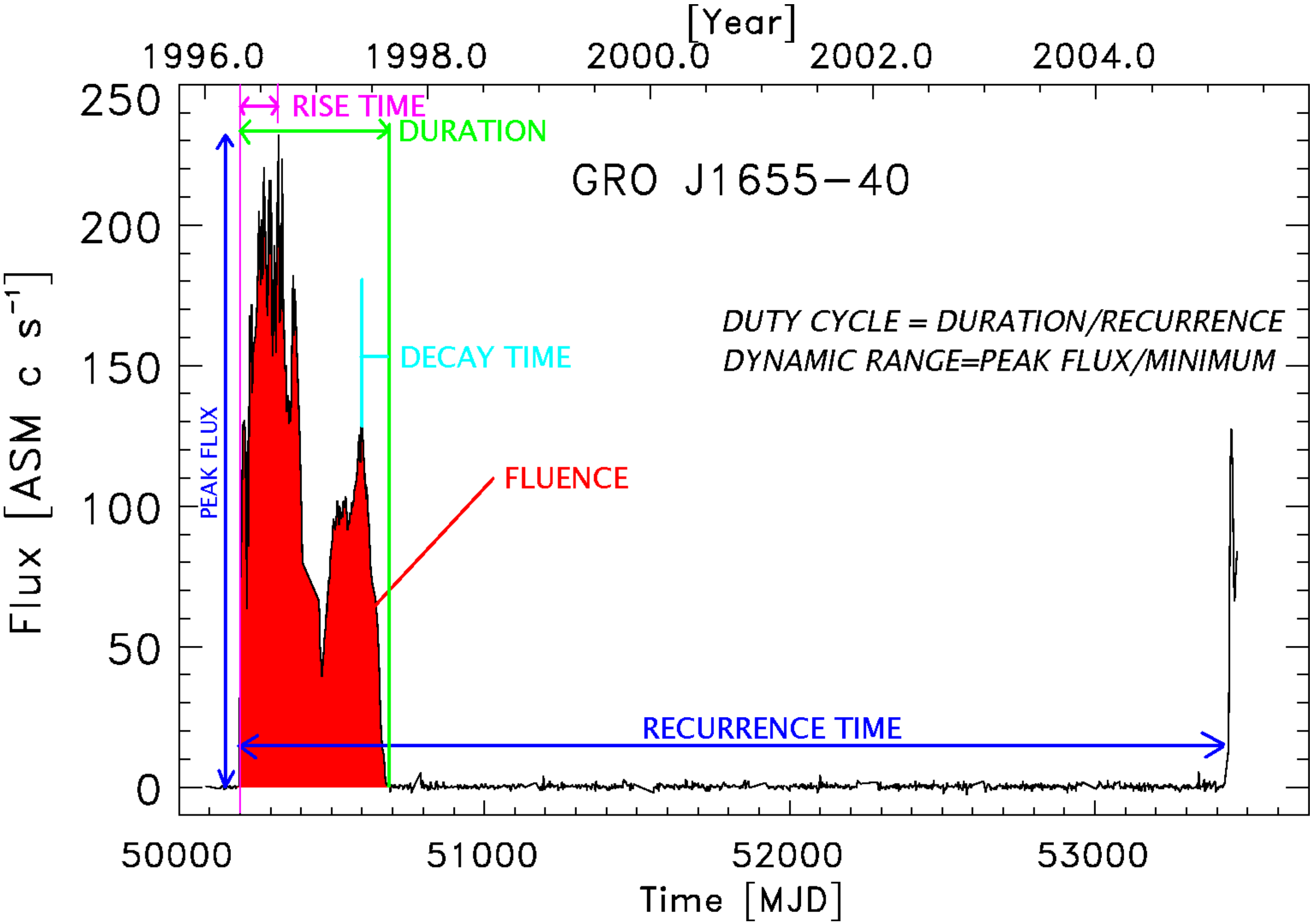
- Signal from a star that comes and goes (and may or may not return) on a time scale shorter than a human lifetime (i.e., much shorter than the shortest stellar lifetime)
- fundamentally: an instability that is observable for a few years at most, giving rise to either electromagnetic radiation, gravitational radiation, neutrino flux (i.e., signals that are not distorted beyond recognition on their way to the detector, unlike cosmic rays)
- stellar transient -> involving objects of 0.1-100 solar masses

What makes transients interesting?

- they show that we are living in a dynamic universe, even on human time scales
- they involve physical phenomena otherwise unobservable
- they probe luminosities otherwise unattainable which can provide a powerful diagnostic for the object itself and its surroundings
- they show the same object in a broad range of circumstances -> powerful diagnostic
- for some classes of objects, transients form an important fraction of the population. Their study thus reveals important info on that population

Parameters

- Peak flux → naturally limited by Eddington limit
- Fluence → total energy output
- Rise time → instability active
- Duration
- Decay time → returning to equilibrium
- Recurrence time → build-up to instability
- Duty cycle
- Dynamic range



RXTE/ASM

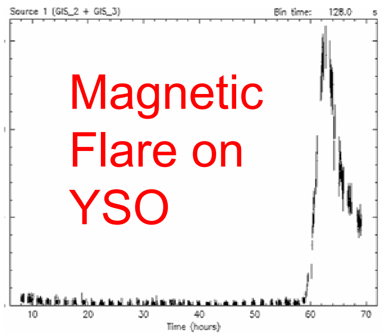
Overview of stellar transients

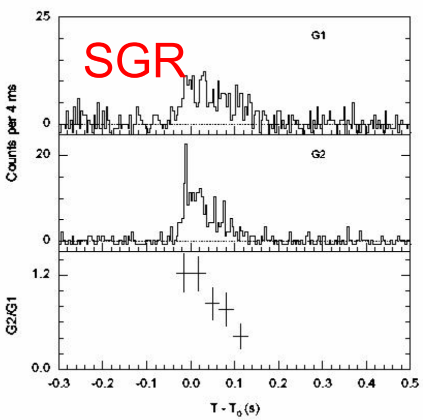
Type	Kind
Flares on dwarf M star, PMS stars, RS CVn's, Sun	Magnetic reconnection (1 per sq deg per day)
SGR/AXP bursts	Magnetic reconnection
Type II X-ray bursts	Magnetic reconnection?
Dwarf nova	Accretion disk instability
Soft X-ray transient	Accretion disk instability
Hard X-ray transient	Eccentric wind accretion
Supergiant FXT	Clumpy wind accretion
Stellar tidal disruption event	Accretion of star by SMBH
Eruptive LBVs	Hydrodynamic envelope instability
Type-I X-ray burst	Thermonuclear shell flash
Superbursts	Thermonuclear shell flash
Nova	Thermonuclear shell flash
Supernova Ia	Thermonuclear core flash
Core-collapse SNe	Gravitational collapse
Gamma-ray burst	Gravitational collapse (+stellar merger?)

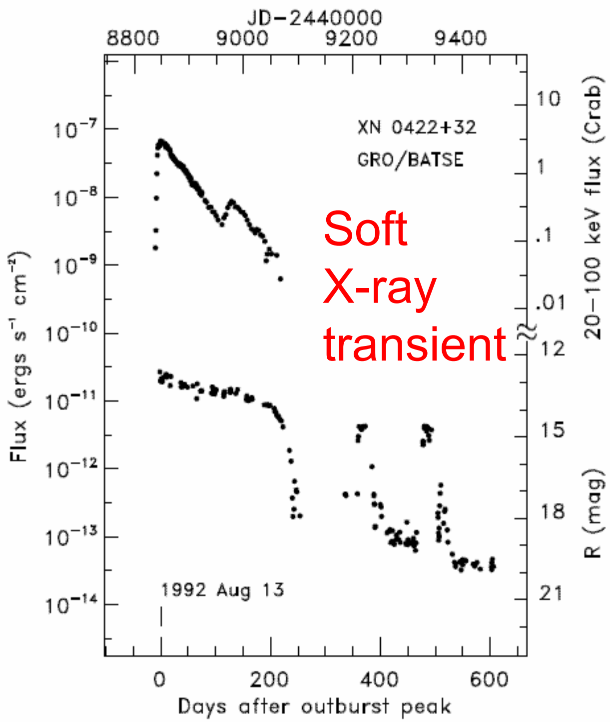
Color coding with energy source: magnetic, gravitational or thermonuclear

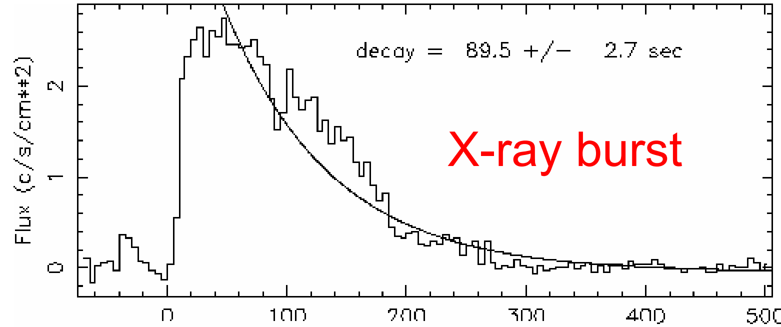
Examples of light curves of various kinds of transients

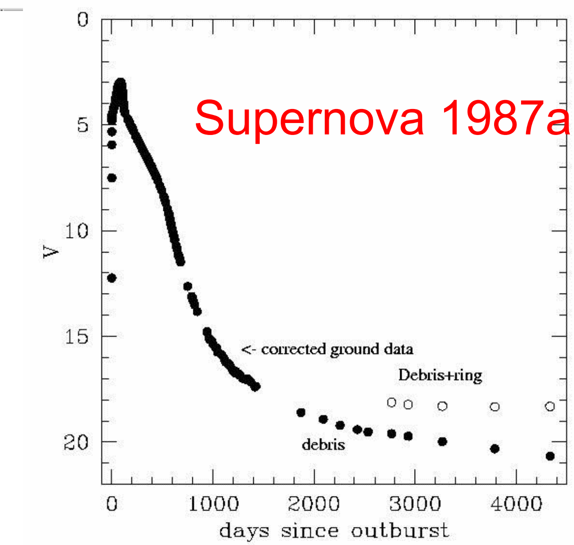
(note diversity in time scales)

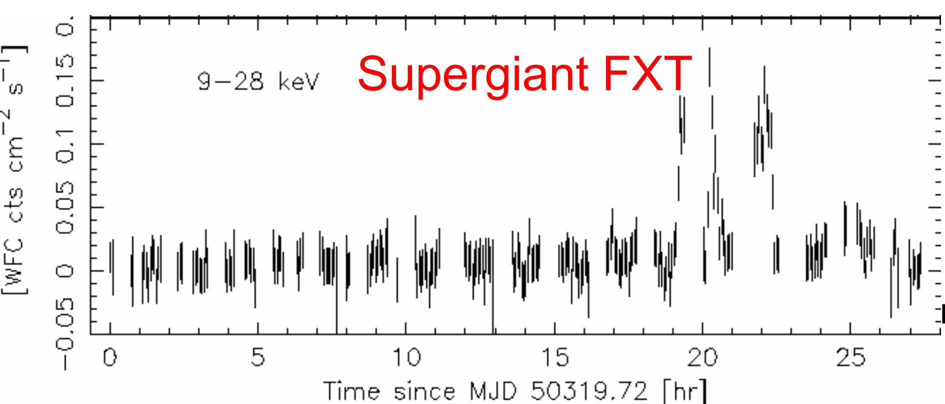


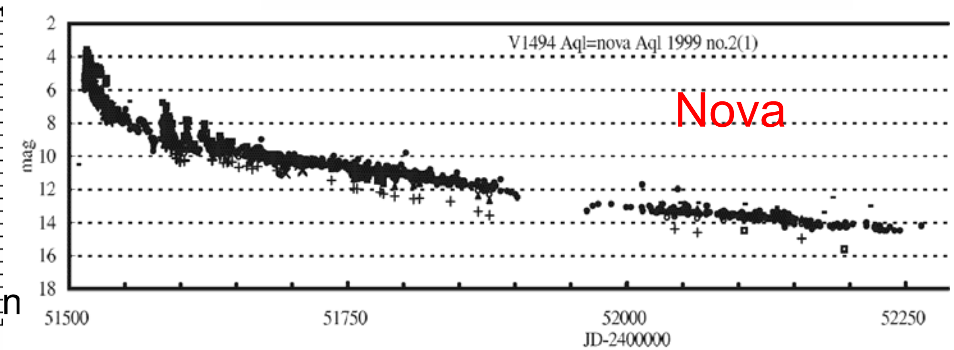












Overview of transients light curve chars

(Note that there may be a tranquil component underneath the transient one)

Type	Rise time	Duration	Recurrence
Flares	<10 s	10 s – few days	mins – weeks
SGR bursts	< 1 ms	1-1000 ms	>0.2-1400 s
SGR giant bursts	<1.5 ms	0.1 s	decades?
Type-II X-ray bursts	<1 s	2-700 s	7 s – 1 hr
Dwarf novae	< 10 d	1 – 20 days	~100 d
SXTs	<20 d	days – years	100 d – 50 yr
HXTs	< few days	days – weeks	weeks – years
Supergiant FXT	<1 min	Hours	Days to years
Stellar tidal disruption event	1 month	years	(destructive)
Eruptive LBVs	yrs	Yrs to decades	Hundreds yrs
X-ray bursts	<10 s	10 – 3000 s	> 2 hr
Superbursts	few s	2 – 12 hr	0.2-10 yr
Classical novae	Few days	months – 40 yr	10^4 yr?
GRBs	<1 ms – 1 min	0.1 s – 1 hr + afterglow	(destructive)
SNe	?	year	(destructive)

Energetics and time scales

Type	Typical duration	Char T (keV)	Peak luminos. (max)	Peak fluence (max)
Solar flare	< 1 s, hour	10	10^{28} erg s^{-1}	10^{23-32} erg
SGR bursts	100 ms	30	10^{42}	10^{41}
SGR giant bursts	500 ms	30	10^{47}	10^{46}
Type II X-ray bursts	30 s	3	10^{38}	10^{40}
Dwarf novae	weeks	0.05	10^{38}	10^{44}
Soft X-ray transient	weeks	1	10^{39}	10^{45}
Hard X-ray transient	weeks	15	10^{33-38}	10^{40-45}
Stellar tidal disruption event	years	0.1	10^{45}	10^{52}
Eruptive LBV SN imposters	decades	0.001	10^{40}	10^{51}
Type I X-ray bursts	100 s	2	10^{38}	10^{39}
Superbursts	12 hours	2	10^{38}	10^{42}
Classical novae	weeks	0.04	10^{38}	10^{46}
GRBs (prompt)	100 s	300	10^{53} (iso)	10^{54} (iso)
Supernovae	months	0.001	10^{43}	10^{51}

human consumption 10^{13} erg s^{-1}; Sun 10^{33} erg s^{-1}; solar rest mass 10^{54} erg; 10 Megaton TNT = 4 x 10^{23} erg = class 8 earthquake = Mt St Helens; "foe" = fifty-one equivalent

Transients and signal carriers

Carrier	Transients seen?
Neutrinos	Only SN 1987a
Gravitational radiation	None
Radio waves	Just beginning, with some transient radio pulsars (RRATS), accretion events, YSOs, SNe
Infrared radiation	Just beginning, SNe at high redshift
Visual light	(super)novae, flare stars
UV	Novae, flare stars, tidal disr evts
X-rays	Yes, accreting compact objects, flare stars, GRBs, SGRs
Gamma-rays	Yes, compact objects & GRBs

Observations of transients

- Find a transient, either intentionally or serendipitously
- (optional) Alert the community through IAU circulars, Astronomical Telegrams, GCN circulars, or automated systems
- Follow up peak through accepted programs with specific instrumentation to measure spectrum and variability and diagnose transient, fine tune further follow up
- Monitor the decay, to detect change of behavior
- Follow-up in quiescence, to determine environment
- Do archival searches, find progenitor

Find transients

- Transients mostly occur at unexpected locations in the universe -> maximize covered volume of universe → go wide-field and/or deep
- The sensitivity needs to be a match to the expected peak flux, if oen is searching for particular kinds of transients
- The bandpass needs to be a match to the expected peak spectrum (e.g., thermonuclear shell flashes on NSs are brightest in X-rays, supernovae in the optical cq IR for high redshifts).

Important search parameters

- Field of view
- Sensitivity
- Etendue or grasp: collecting area (prescribing depth of observation) times solid angle (prescribing width)
- Cadence: sampling scheme
- Bandpass

Searching in X-rays: often wide FOV, but moderate collecting areas

All-sky monitors:

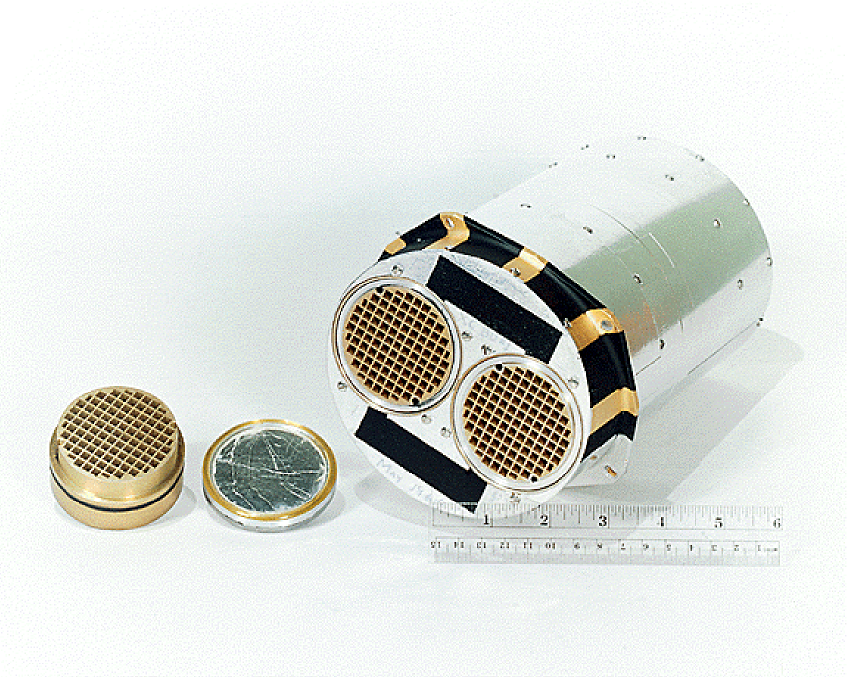
Satell.	Operations	Bandpass	Resol.	FOV	T(75%)	Sens.
Vela 5b	'69-'79	3-12 keV	6 deg	0.05% of sky	56 hr	40mCrab
Ariel V	'74-'80	3-6	10	1%	1.5	200
Ginga	'87-'91	2-20	0.2	0.05%	48	50
Granat	'89-'94	6-180	2	75%	0	100
Compton	'91-'00	20-300	5	75%	0	1000
RXTE	'96-	2-10	0.2	5%	2	30
MAXI	'09	0.5-30	1.5	2%	1.5	15

Wide field imagers:

Satell.	Operations	Bandpass	Resol.	FOV	Sens.
MIR/COMIS	'88-'99	2-30 keV	0.03	2%	5 mCrab
BSAX/WFC	'96-'02	2-30	0.1	7%	10
HETE/WXM	'01-'07	2-30	0.2	9%	100
I'GRAL/IBIS	'02-	15-300	0.1	5%	50
SWIFT/BAT	'04-	15-300	0.1	10%	50

Example 1 of X-ray monitor: The pioneering monitor on Vela-5B

- Six pairs of Vela satellites were launched in 1963-1970 to verify the USA/USSR nuclear test ban treaty
- Active 1967-1979
- Small collecting area (10 cm device)
- Sufficient sensitivity to see the brightest X-ray transients
- Detected the first gamma-ray and X-ray bursts ever
- Large field of view, but without imaging capability



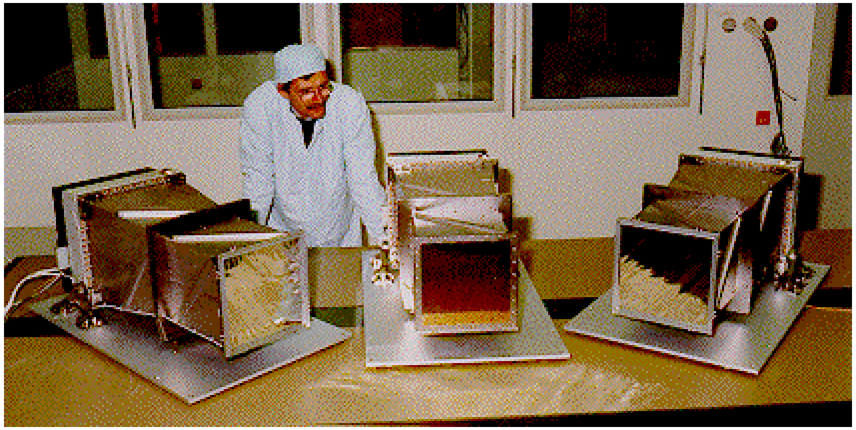
Vela 5B movie of X-ray sky in 1969

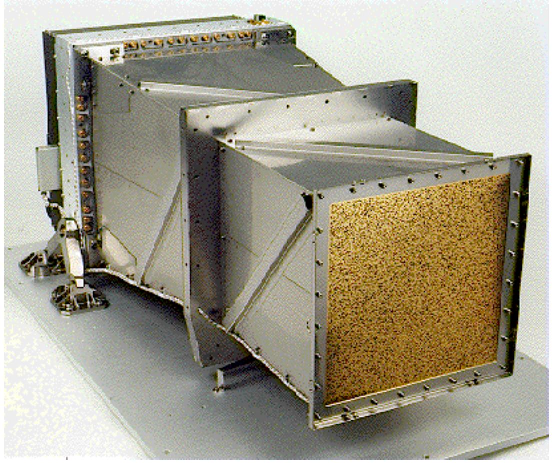
This movie shows the X-ray transient Cen X-4 which contains the nearest accreting neutron star at 1 kpc. It is therefore the subject of many studies even when it is in quiescence. After 1969 it flared only one more time: in 1979.

Movie available at website

Example 2: The Wide Field Cameras on BeppoSAX

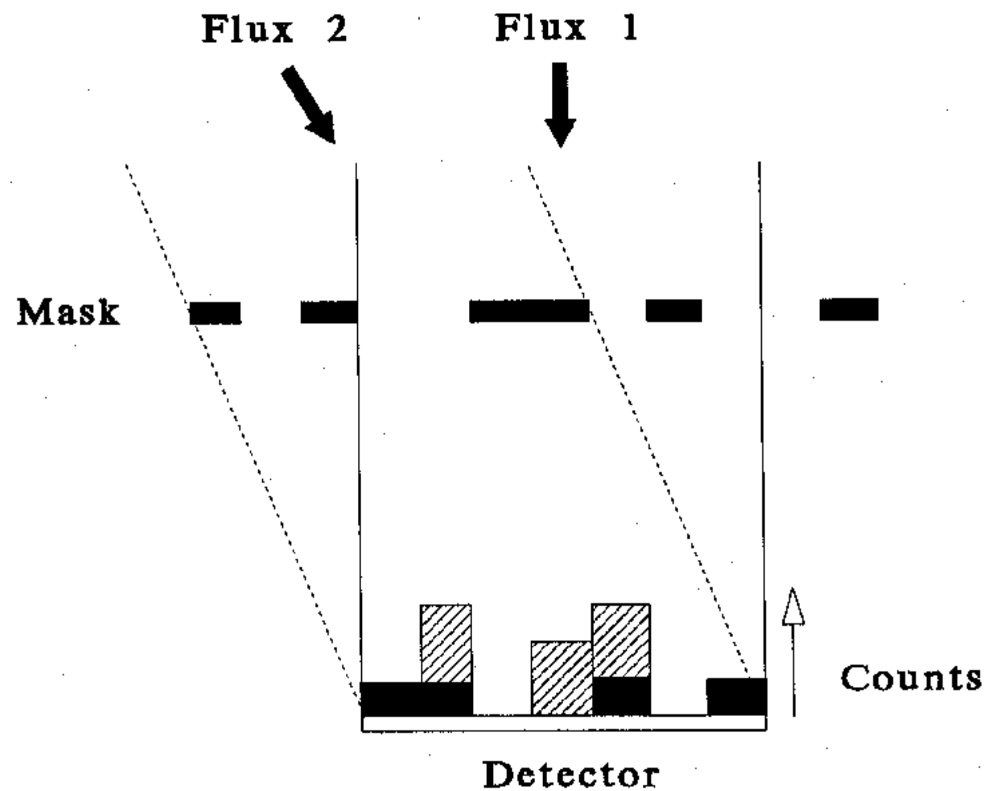
- Built at SRON Utrecht
- Operational 1996-2002 on the Italian/Dutch BeppoSAX X-ray observatory
- 40 x 40 square degree field of view
- Imaging device, employing 'coded aperture imaging'
- 5 arcmin resolution
- 2-30 keV bandpass, sophisticated proportional counter
- Enabled for the first time measurement of GRB distance scale, revolutionizing GRB research 30 years after Vela discovery



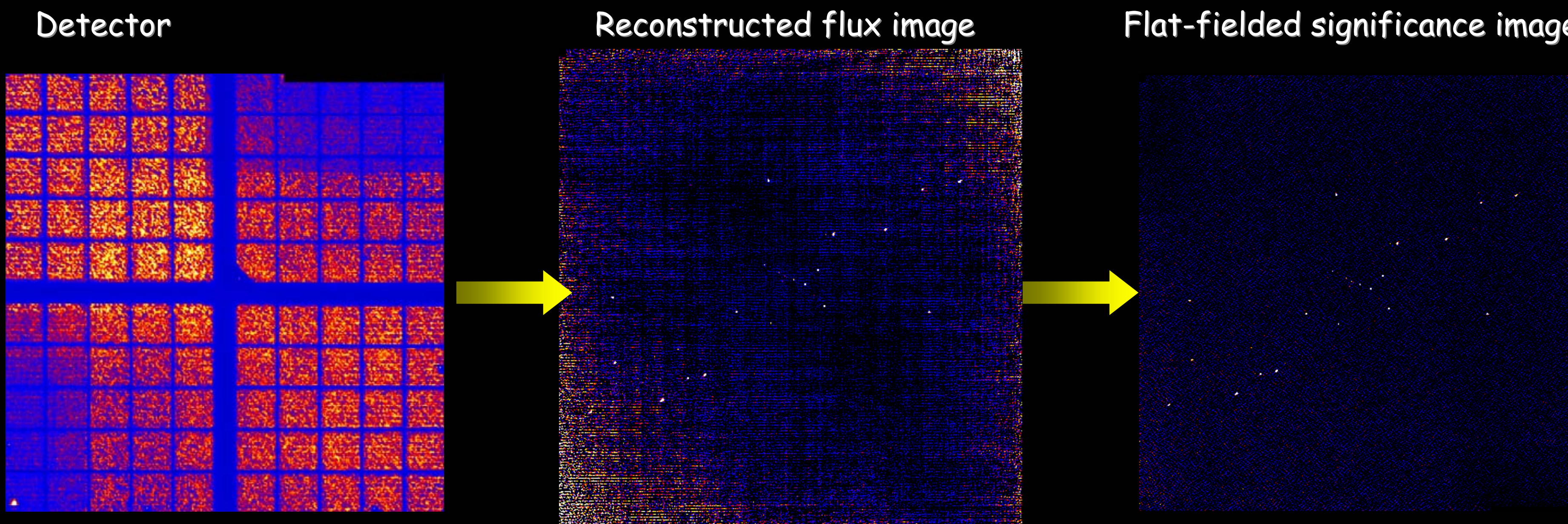


Wide X-ray FOV → traditional optics not applicable because X-rays can only be reflected at grazing angle of less than 1 degree. Alternative: coded aperture imaging principle

- Multiple-pinhole camera
- Pinhole size determines angular resolution
- Number of pinholes determines sensitivity
- Indirect (2-step) imaging algorithm
- Quality of sky image reconstruction depends strongly on pattern of pinholes
- Number of objects should be smaller than number of pinholes, otherwise sky is formally not uniquely determined



Coded aperture imaging principle, illustrated with real WFC data on Galactic center



- The detector measures multiple shadows of point sources in the field of view → an encrypted image of the sky. The left image shows two clear shadows. 20 other shadows are less obvious and only become apparent after a full quantitative analysis
- The decryption (2^{nd} and 3^{rd} figure) were carried out after the observation on the ground

Searching at optical wavelengths → something new..

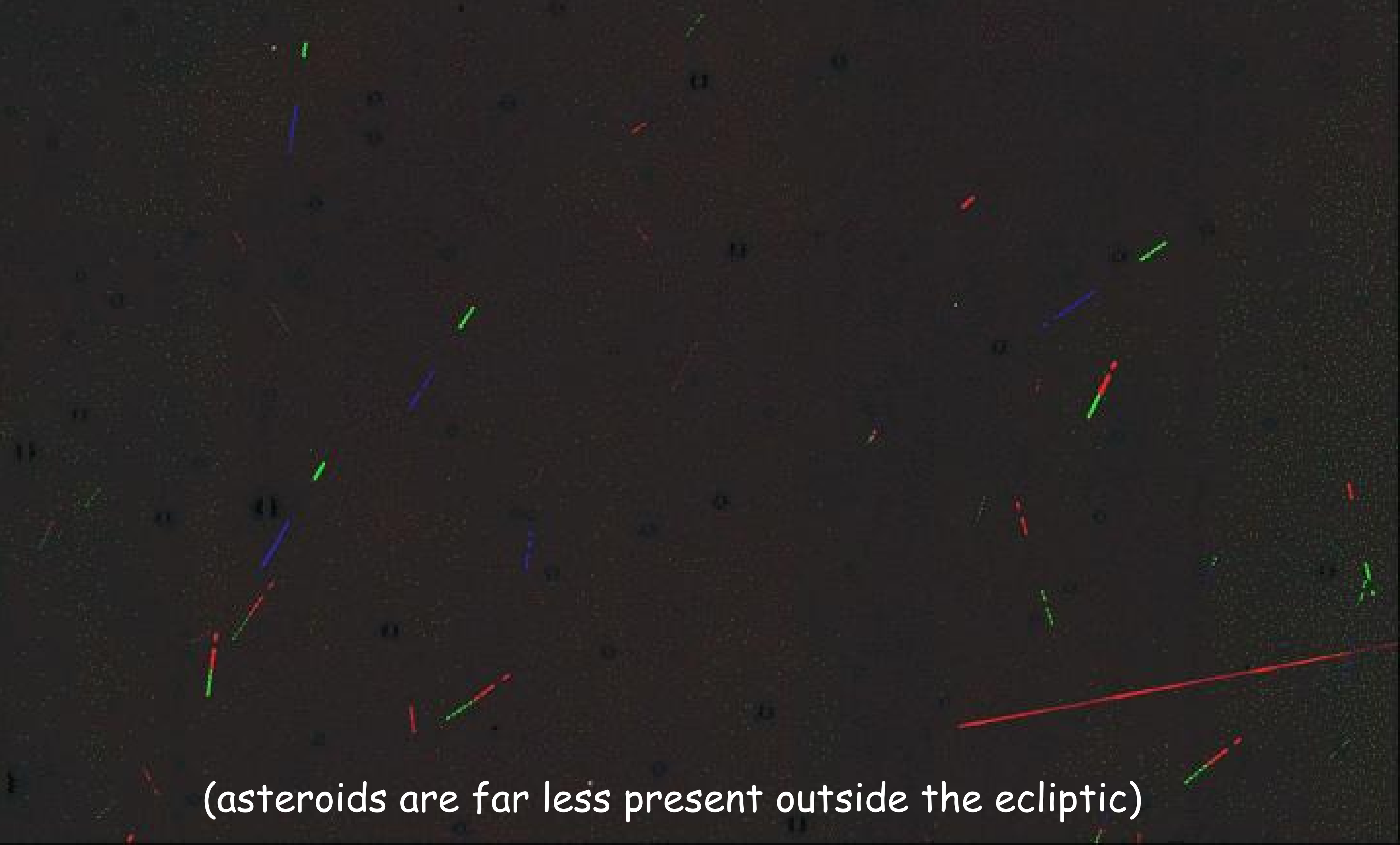
Site	Telescope	Diameter (m)	Instrument	FOV
Paranal	VLT	4×8.2	FORS	0.01
	VST	2.4	OmegaCam	3.75
La Silla	NTT	3.6	SUSI	0.01
	WFI	2.2	CCD	0.32
Tololo	Blanco	4.0	MOSAIC	0.36
	SOAR	4.1		
Las Camapnas	Magellan	2×6.5	MagIC	0.001
Pachon	GEMINI	8.1	GMOS	0.01
La Palma	WHT	4.2	PFIP	0.07
	NOT	2.6	ALFOSC	0.01
Mauna Kea	KECK	2×10	LRIS	0.01
	SUBARU	8	Suprime-Cam	0.25
	GEMINI	8.1	GMOS	0.01
Mt Hopkins	MMT	6.2	Megacam	0.16
Mt Graham	LBT	2×8.4	CCD	0.25
Kitt Peak	Mayal	4	MOSAIC	0.35
	Spacewatch	1.8	CCD	0.32
Calar Alto		3.5	CHARM	
Sutherland	SALT	11	SALTICAM	0.01
Palomar	NEAT	1.2		3.75
	P60	1.5	CCD	0.05
	Hale	5	LFC	0.16
Zelenchuk	BTA	6	CCD	0.003

This table shows parameters of a few commonly used telescopes. They all have small FOVs / large collecting areas. Large FOVs are something new in the optical and can only be reached by large-sized detectors (CCD cameras). This is currently a challenge in technology development.

- List of largest telescopes on earth and plans: http://astro.nineplanets.org/bigeyes.html

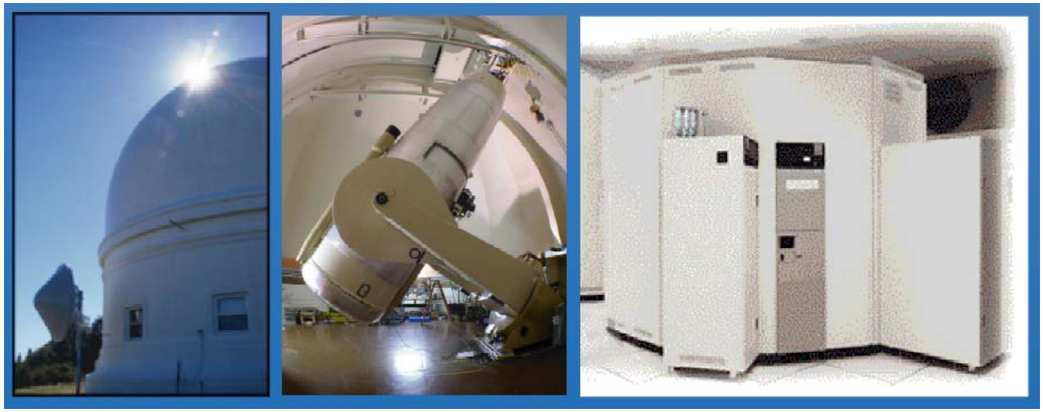
Searches of stellar transients in the optical suffer from one particular source of noise: ASTEROIDS. This 1 square degree image in the solar system ecliptic shows many such noise features, see next slide

Subtract late image from early image as depicted in previous slide: get rid of static stars → make visible plenty of moving asteroids



(asteroids are far less present outside the ecliptic)

Example 1 of searching in optical: going wide in the 'nearby SN factory'



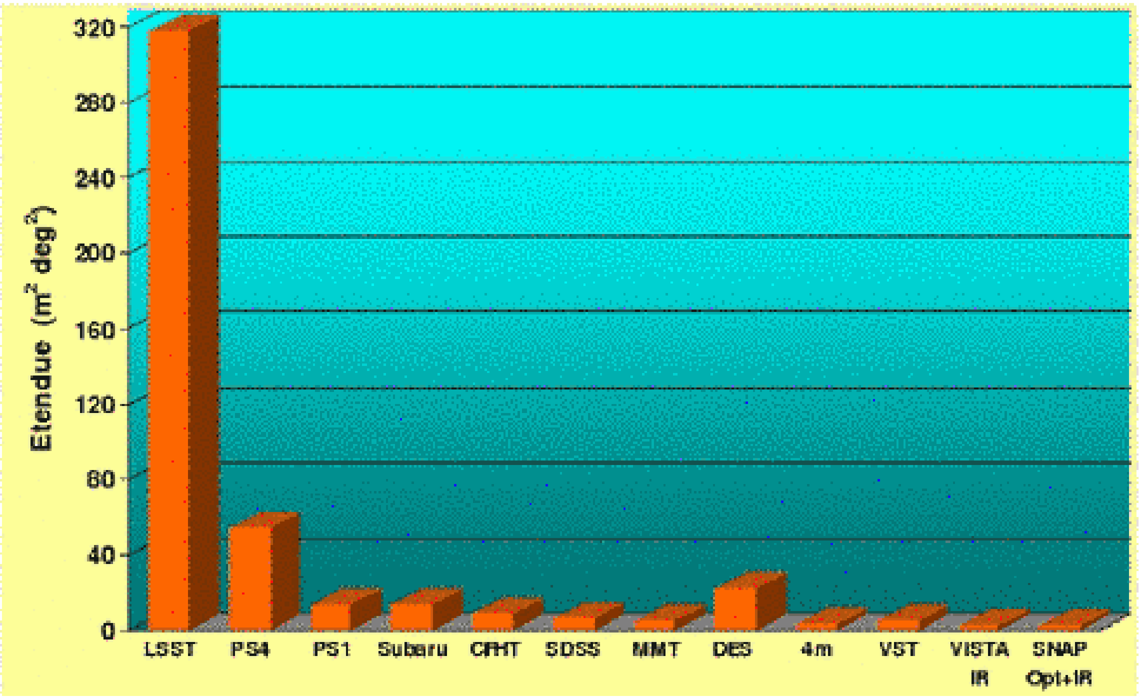
- Turn noise-problem (see previous slides) around: hop on wide-field searches for asteroids
- NEAT uses telescope on Hawaii and Palomar to image 500 sq deg per night → identify on average 25 SN candidates per night
- Do 1-m follow-up photometry to find candidates with right brightening rate, exclude half
- Do 2-m (also on Hawaii) spectroscopy of ~10 candidates per half-night

Example 2: going wide AND deep in optical / future: PAN-STARRS

- Pilot to proposed Large Synoptic Survey Telescope (LSST)
- Under design/construction of prototype telescope
- 4 x 1.8-m telescopes (cheaper than 1 x 3.6 m)
- 3-deg FOV; etendue 70 m^2 deg^2
- Scan 6000 sq deg per night at 1 min exposures down to a limiting magnitude of 24; cadence: whole sky in 1 week
- 1.4 Giga-pixel CCD cameras
- Primary science goal: find hazardous asteroids
- 5000 SNe every year
- illustration

Example 3: Large Synoptic Survey Telescope

- 8.4 m, r<24.5 in 30 s, 10 sq deg, 3 billion pixel camera
- Cadence: whole sky every 3 nights in 2 bands
- 10^5 SNe per year
- Extendue: 300 m^2 deg^2
- 10,000 sq deg / 30 TB per night
- First light >2014



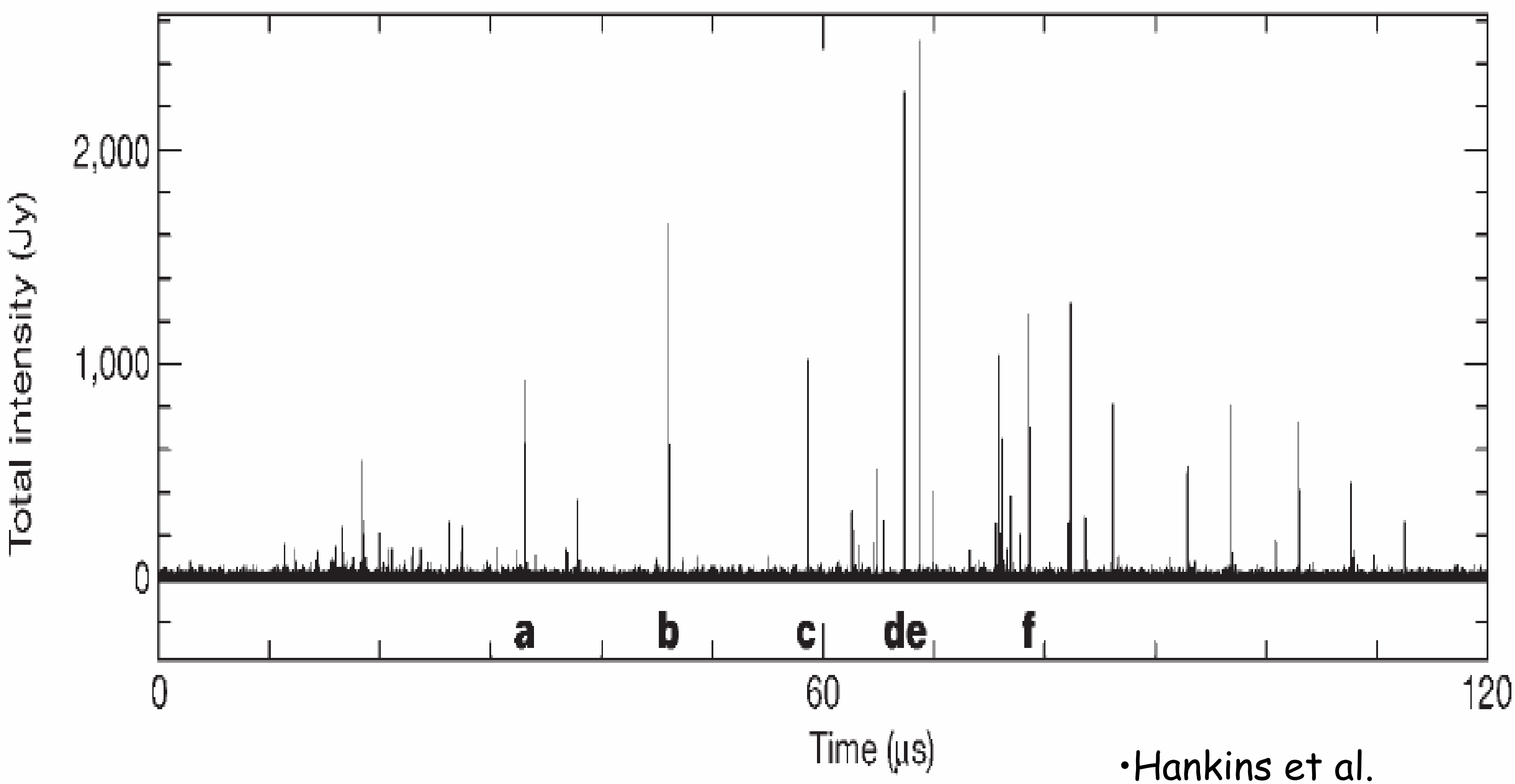
Searching in radio: 2-dim interferometers

- Single-dish/single antenna yields no image, unless scanning
- Interferometers do produce images. WSRT is 1-dim: takes half a day do produce an image; VLA is more 2-dim (tri-arm shaped)
- 2-dim interferometers can make semi-instantaneous images → LOFAR, ALMA, ATA …

Performances of radio telescopes @ 1 GHz

Telescope	FOV (linear degrees)	Resolution (arcmin)	Collecting area (m^2)	Remark
Allen Telescope Array	2.5	1.3	10^4	
LOFAR	90	0.1	10^{4-5}	0.1 GHz
WSRT	0.5	0.2	10^4	
VLA	0.5	0.02	10^4	
ALMA	0.02	0.0002	10^4	300 GHz

Shortest stellar transient ever detected was detected in the radio: < 2 ns! (Crab nebula+pulsar with extremely fast readout) → promises discoveries in other sources, also at other wavelengths



•Hankins et al. 2003

Channels for alerting the community about transients

- Central Bureau for Astronomical Telegrams → IAU circulars
  - Since 1880
  - Telegram operations ceased in 1993, now internet
  - Main channel for reporting comets, minor planets orbits, (super)novae
  - Delay of hours to days between submission and publication
- GCN notices: fully automatic formatted distribution of GRB coordinates; through email and socket messaging (since 1993) (formatted numbers; see next slide)
- GCN (Gamma-ray burst Coordinates Network) circulars: instantaneous publication for particularly GRBs, via email (since 1998) (grammatically correct text)
- Astronomers TELegrams: instantaneous publication for particularly (super)novae; on internet and optionally via email (since 1997)
- IBAS messaging: as GCN, but only for European INTEGRAL satellite and no email (since 2002)

Example of a GCN notice

```
TITLE:           GCN/SWIFT NOTICE
NOTICE_DATE:     Sat 04 Sep 04 19:42:25 UT
NOTICE_TYPE:     Swift-BAT GRB Position
TRIGGER_NUM:     100002,   Seg_Num: 0
GRB_RA:           68.95d {+04h 35m 47s} (J2000),
                  68.99d {+04h 35m 57s} (current),
                  68.50d {+04h 34m 01s} (1950)
GRB_DEC:         -37.30d {-37d 18' 13"} (J2000),
                 -37.29d {-37d 17' 39"} (current),
                 -37.40d {-37d 24' 16"} (1950)
GRB_ERROR:       4.00 [arcmin radius, statistical only]
GRB_INTEN:       4591 [cnts]    Peak=933 [cnts/sec]
BKG_INTEN:       6455 [cnts]
BKG_TIME:        45384.00 SOD {12:36:24.00} UT
GRB_DATE:        13243 TJD;   239 DOY;   04/08/26
GRB_TIME:        45400.44 SOD {12:36:40.44} UT
GRB_PHI:         154.14 [deg]
GRB_EL:           43.60 [deg]
TRIGGER_INDEX:   127
SOLN_STATUS:     3
RATE_SIGNIF:     18.63 [sigma]
IMAGE_SIGNIF:    14.79 [sigma]
MERIT_PARAMS:     +1  +0  +0  +0  +3 +33  +0  +0  +6  +1
SUN_POSTN:       155.52d {+10h 22m 05s}  +10.18d {+10d 11' 02"}
SUN_DIST:         93.43 [deg]
MOON_POSTN:      286.97d {+19h 07m 53s}  -27.40d {-27d 23' 53"}
MOON_DIST:       106.13 [deg]
GAL_COORDS:      239.98,-42.17 [deg] galactic lon,lat of the burst direction
ECL_COORDS:       57.00,-58.36 [deg] ecliptic lon,lat of the burst direction
COMMENTS:        SWIFT-BAT GRB Coordinates.
COMMENTS:        This is a rate trigger.
COMMENTS:        A point_source was found.
COMMENTS:        This does not match any source in the on-board catalog.
COMMENTS:        This does not match any source in the ground catalog.
COMMENTS:        This is a GRB.
```

```
GCN/SWIFT-BAT
GRB Position
RA=68.988d  DEC=-37.295d
ERROR=4.0arcmin
TIME: 12:36:40.44 UT
R_Signif=18.6
I_Signif=14.8
```

Nearly the same content, and the same format across all types.

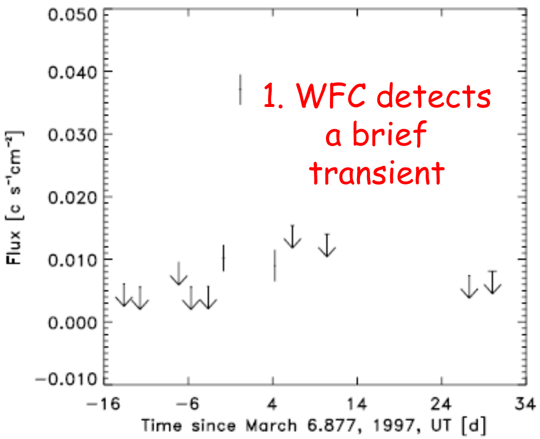
Follow-up

- = measure (time-resolved) spectrum (characterization of continuum, temperature and abundance measurements, velocity measurements), variability ([quasi-]periodicities, intrinsic noise, fastest changes), polarization measurements (indicative of e.g. significant magnetic fields)
- purpose: typify source, measure distance and energies,
- sometimes involves dedicated instruments, particularly for SN (e.g., SN factory) and GRB searches (small robotic telescopes like REM, Raptor, LOTIS), but mostly dedicated programs on general-purpose telescopes

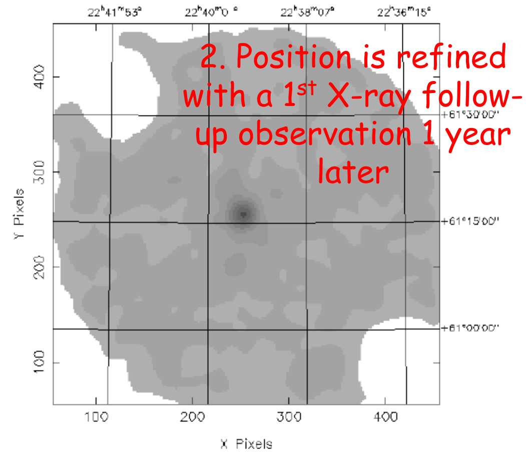
Example of fast follow up: the time line of GRB 060218

- 18 feb 2006, 3:36:02 UT: Swift-BAT sees faint “possible”burst. Located with 3 arcmin accuracy (90% conf) → GCN notice sent out 1.1 s later
- +97 s: ROTSE optical telescope in USA on target, sees high flux at +690 s
- +153 s: Swift X-ray telescope and UV telescope on target
- +3219 s: GCN Circ with announcement of optical afterglow
- +7.3 hr: GCN Circ with X-ray transient
- +22.3 hr: MDM 2.2 m taking spectrum
- +23.4 hr: GCN Circ with announcement of host galaxy
- +42.3 hr: GCN Circ stressing peculiarities
- +44.4 hr: Very Large Array (radio telescope) on target
- +48.0 hr: GCN Circ with MDM-measured redshift: 0.0331 → nearby!
- +48.8 hr: GCN Circ with VLA detection
- +85 hr: GCN Circ with discovery of supernova spectral features
- +25 d: first paper on astro-ph
- 68 GCN circulars, 128 papers (April 2008). This turned out to be one of only four GRBs coincident with a supernova

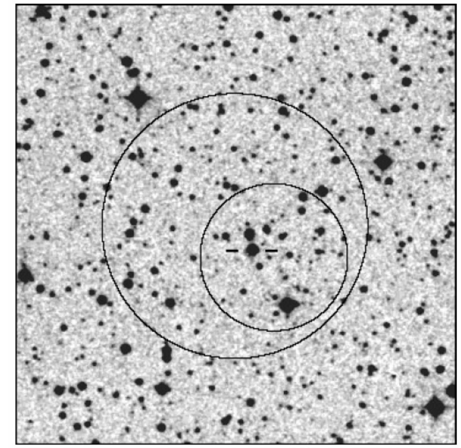
Example of slower follow up: SAX J2239.3+6116



1. WFC detects a brief transient

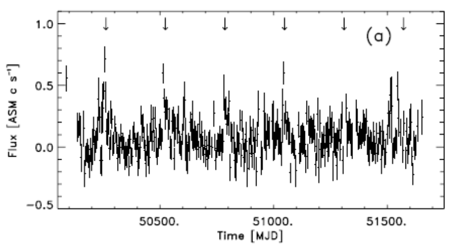


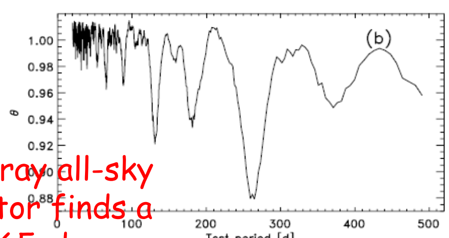
2. Position is refined with a 1st X-ray follow-up observation 1 year later

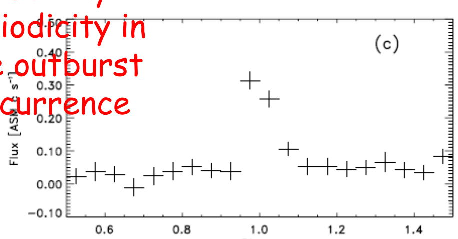


3. Spectra were taken of the three brightest stars in the X-ray error region

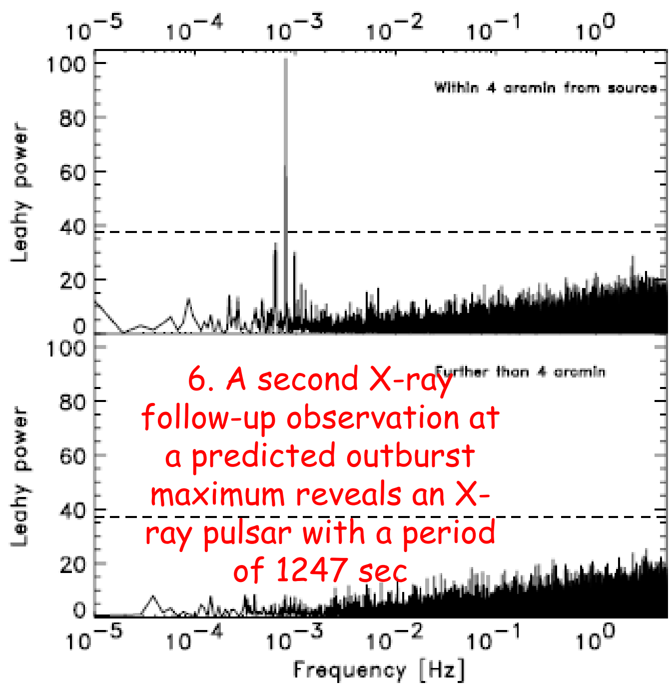
4. Only one star showed an H-alfa emission line, indicative of an active accretion disk



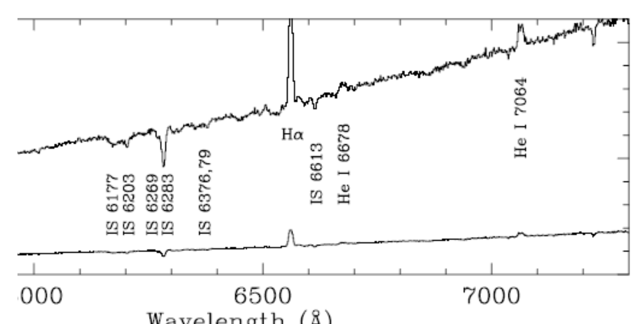




5. X-ray all-sky monitor finds a 265-day periodicity in the outburst recurrence



6. A second X-ray follow-up observation at a predicted outburst maximum reveals an X-ray pulsar with a period of 1247 sec



7. Summary: observation collected over 3 years unearthed one of the slowest high-mass X-ray binaries: pulsar period 1247 s / orbital period 265 d

Future may bring problem keeping up with discovery rate

- Current discovery rates (yr^{-1}): 200 SNe, 50 GRBs, 10s of (dwarf) novae etc.
- Discovery rate is expected to increase dramatically with PAN-STARRS, LSST and radio developments (e.g., for LSST 10^5 SNe annually!)
- Data rates high (e.g., tens of TB/night for LSST)
- Sofar, follow-up efforts have been more or less ad-hoc
- Follow-up instrumentation combined over the world has limited exposure budget which will be insufficient for follow-up in the future → need to select
- Community is thinking about intelligent ways to solve this → automatic decision making what to follow up & automatic follow-up for fast events (like already the case for GRBs)

Concluding remarks

- Transients often have a fast rise and slow decay, identifiable as the instability phase and the cooling phase
- Except for GRBs, SNe and possibly tidal disruption events, all transients are Galactic. That does not introduce a serious selection effect: the Galaxy holds rather complete representation of different types of stellar objects
- Our knowledge of transient phenomena is incomplete, because not all wavelength regimes are covered equally as good. For instance, techniques for transient detection in the radio band are just emerging (e.g., LOFAR)
- Transients are not exclusively radiative, but observations of other signals (gravitational waves, neutrinos) are still in the exploratory phase
- This course will concentrate on thermonuclear and gravitational collapse transients