High Precision (Optical) Photometry

What have we learnt and where are we going?

CIT, Ireland

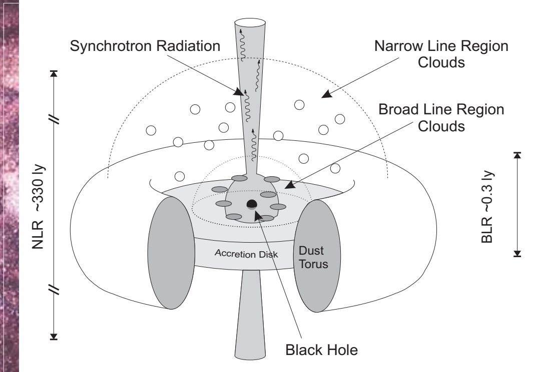
LSW, Germany

Boyden Observatory, South Africa

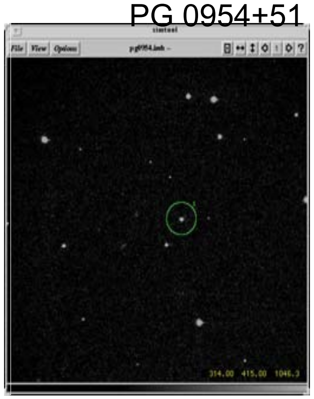
Kryoneri Observatory, Greece

Niall Smith (CIT)

Blazars

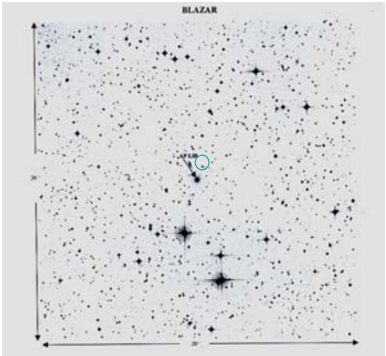


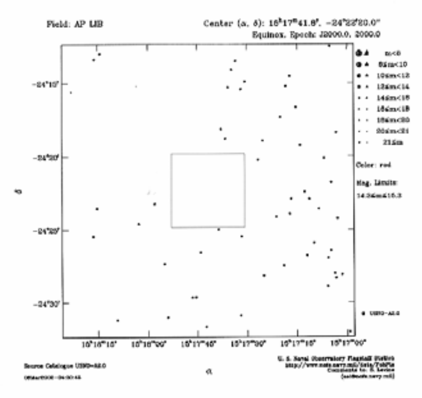
PG 0954+51



Field of AP Lib

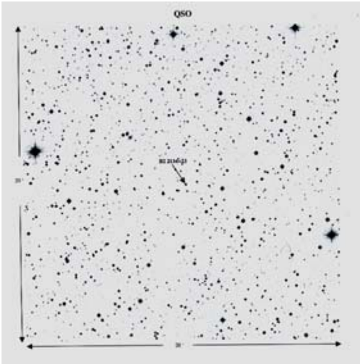
AP Lib

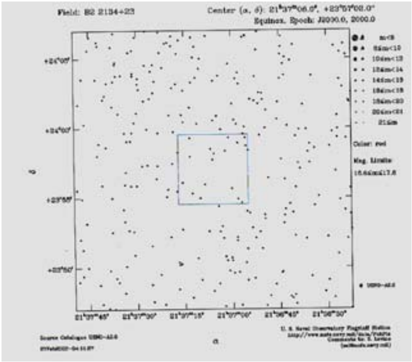




Field of B2 2134+23

B2 2134+23





Science Drivers

The ONLY way to infer structures on timescales of light-minutes in AGN is with photometry / spectroscopy

Blazars are lineless → photometry

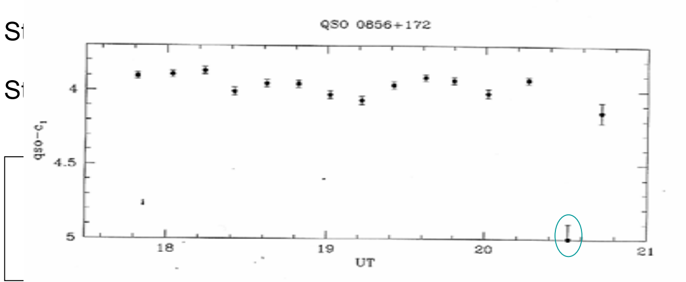
> Photometry on timescales of minutes can probe structures which are three orders of magnitude smaller than even proposed space-borne mm-VLBI

Science Drivers

RELIABLE detection/characterisation of

microflares (ultra-rapid events lasting few minutes)

rapid, small-amplitude events ($T_B >> 10^{12}$ K)



Technical Drivers

RELIABLE CCD photometry of blazars

- during major flares (rare)
- during “quiescent” phases (more common)

PRECISE CCD photometry of blazars

- at mmag level

TIMESCALE of minutes (sampling of seconds)

Long TIME-SERIES to make statistically significant statements

Photon-Limited Detection

Simple example:

If stellar image covers 10 pixels on CCD with a well depth of 350,000 electrons

then

total electron count is 3,500,000

yielding

photometric error of 0.58mmag (~0.06%)

The lure of EMCCDs ……

EMCCD SNR Equation

$$SNR = Q.I.t.F_n.\left[Q.t.F_n.(I + B_{SKY}) + (N_r/G)^2\right]^{-0.5}$$

G = Gain of the Gain Register
F_n = Multiplication Noise factor = 0.5

BUT

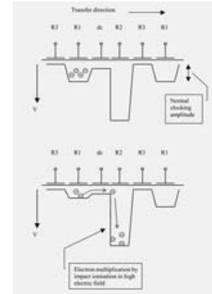
With G set sufficiently high, this term goes to zero

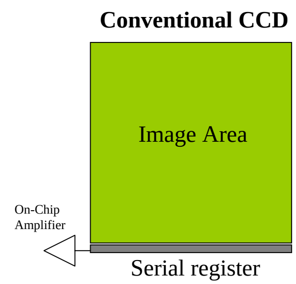
Readout speed and readout noise are decoupled

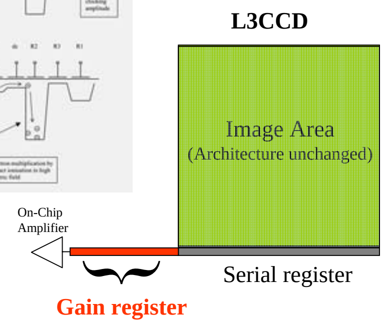
Architecture of EMCCDs

EMCCD readout architecture uses a GAIN REGISTER

- E2V – L3 Vision
- TI – Impactron







EMCCD Engineering Campaigns

2.2m telescope at Calar Alto

7 nights Jan/Feb 2003
6 nights Sept 2003

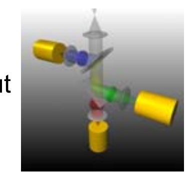
65,949 science frames in January

367,069 science frames in September

L3 (Andor)

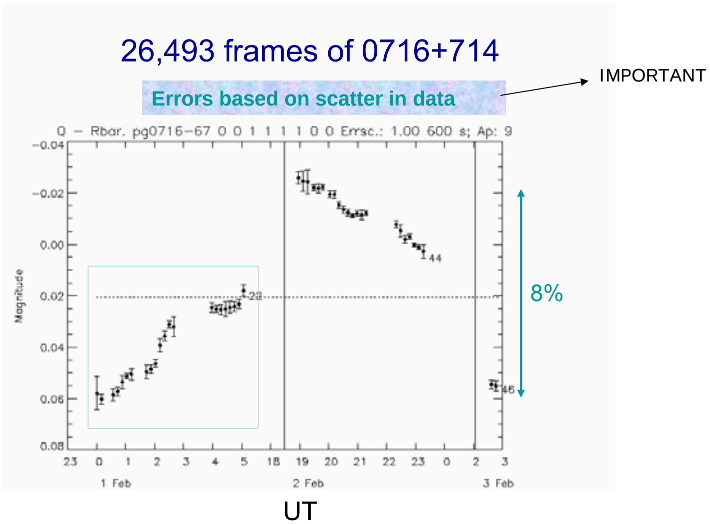
At 4 frames/s a 6-day run generates 690 GIGABYTES of data

Ultracam "Mini-Campaign"

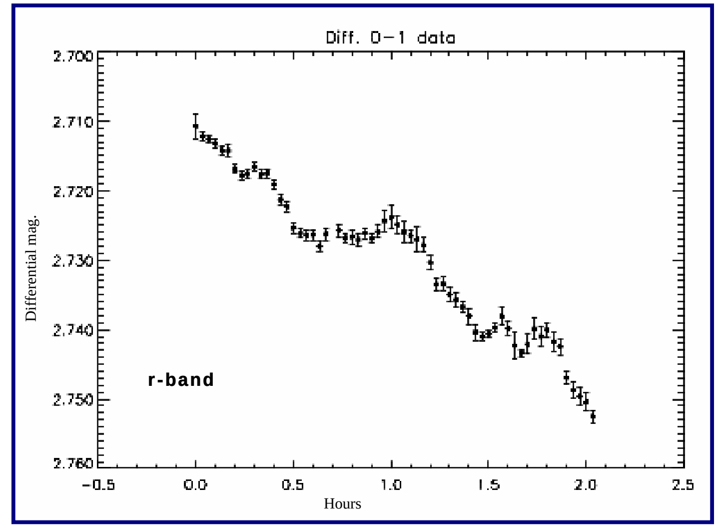


- 3-channel camera capable 4 Mb/s readout
- Three 1k x 1k frame-transfer CCDs
- Observations taken in November 2003 on 4.2m WHT at La Palma in Service Mode
  - Windowed to 100x80 pixels
  - 46,000 science frames per filter = 138,000 frames of data
  - 2 hours of data
- Only one reference star selected by service astronomer
- Similar follow-up observations taken in May 2004

PG0716+714 – EMCCD



PG0716+714 – Ultracam



Generation of Lightcurves

Output is piped to IDL program "qvar"

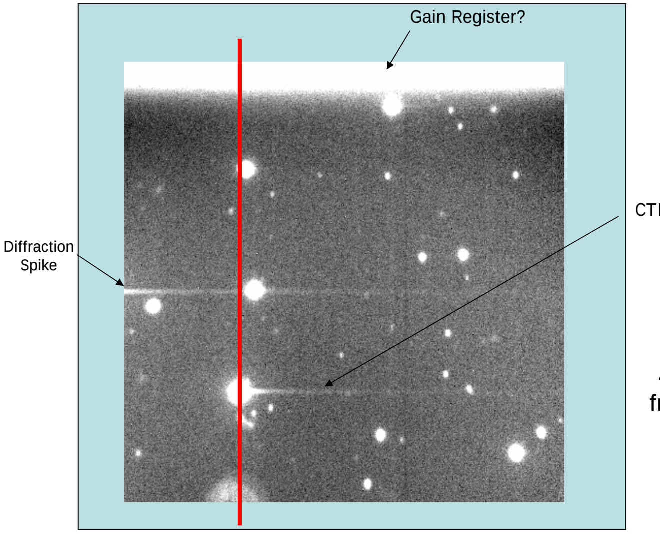
- performs differential photometry using a master reference star (composed of 4-8 stars typically)
- provides statistical tests of variability
- allows different background determination methods to be used
- tracks variations in fwhm, position, apparent magnitude, airmass
- allows rejection of variable stars or data points affected by cosmic rays
- adjust parameters and "see what happens"

FLATTEN
FLATTEN
FLATTEN

Comparison of results?

- Best Photometric precision achieved was +/-1 *mmag* on either 2.2m or 4.2m
- Good S/N on each frame

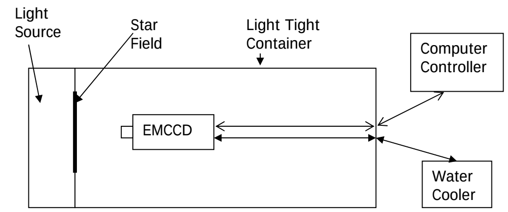
Summed Image of the field of 0716+71



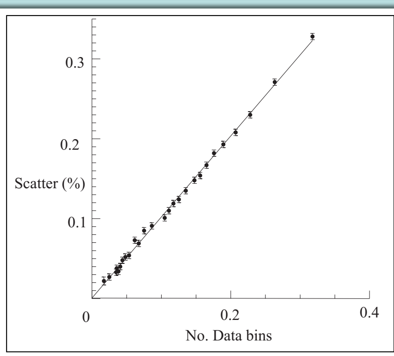
4572 frames

Laboratory Photometric Tests

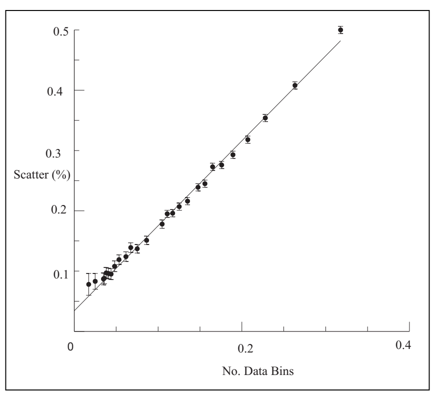
EMCCD



Photometric Analysis



Limiting Scatter in Star1 = 0.01%



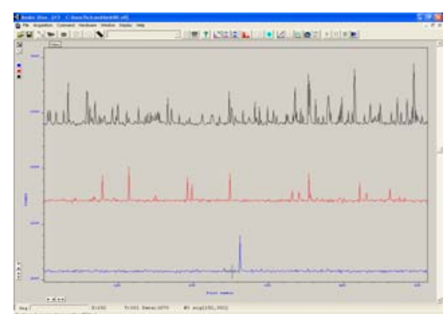
Limiting Scatter in Star2 = 0.03%

Limit to Photometric Precision?

What limits <u>instrumental</u> photometric precision?

- Many parameters to combine
  - Gain, clock voltages, shift speed, etc.

<u>Clock Induced Charge (CIC)</u>

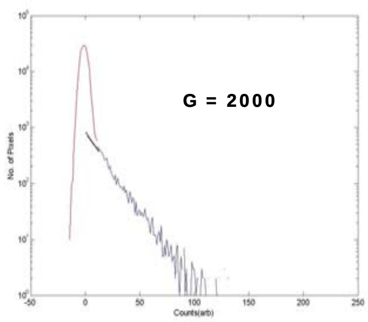


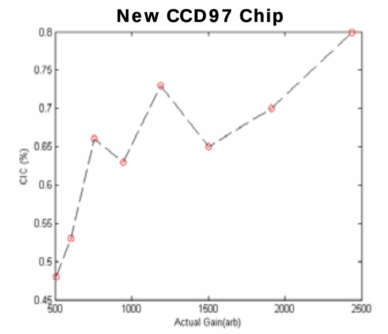
$-30\ ^0C$

$-50\ ^0C$

$-80\ ^0C$

CIC Measured Quantitatively

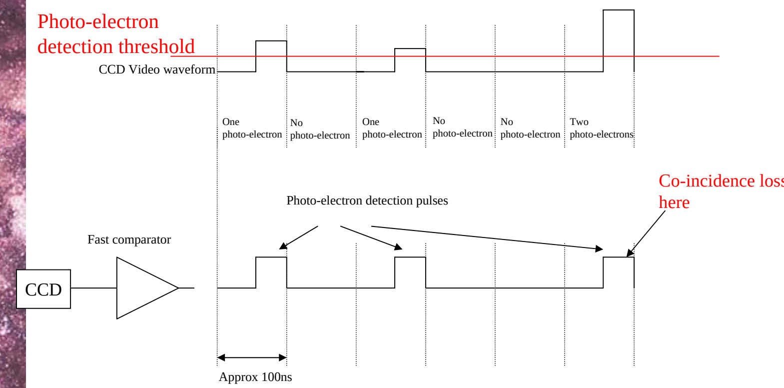




540 frames (1.4 x 10^7 pixels)

CIC < 1%

Removing Multiplication Noise – Photon Counting



$$\mathbf{SNR} = \mathbf{Q.I.t.}\left[\mathbf{Q.t.}(\mathbf{I} + \mathbf{B}_{SKY})\right]^{-0.5}$$

Noiseless Detector !

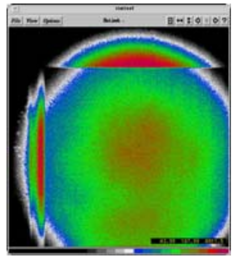
Is the EMCCD the limit??

- Photon statistics
- Sampling
  - inherent plate scale (3 pixels for FWHM)
    - undersampling is really not a good idea – ever!
  - intra-pixel sensitivity
  - changes in seeing
  - crowded fields
    - “pointy” PSF’s are bad
    - non-Gaussian PSF’s are bad

Is the EMCCD the limit??

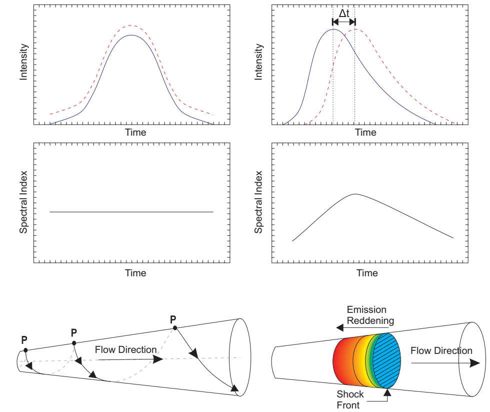
- Comparison stars
  - magnitudes (relative to each other and the source)
  - colour (relative to each other and the source)
  - number
  - isolation (or otherwise)
  - intrinsic stability
- Isolation of object
  - PSF-fitting is inherently an approximation
- Host galaxy contribution
- Optimum aperture
  - variations in PSF across chip

Is the EMCCD the limit??



- Flatfielding
  - integrated counts in the flatfield
  - dangers of a "master flat"
  - flatfield spectrum is not the same as the source
- Tracking accuracy
  - ideally remove the need for flatfielding in differential photometry
- Focussing
  - changes PSF and can lead to non-linear behaviour of object and/or stars
  - defocussing doesn't help in wide-fields as it leads to PSF overlaps of possibly many sources

Next Phase – Testing Emission Models



Two Channel Photometer

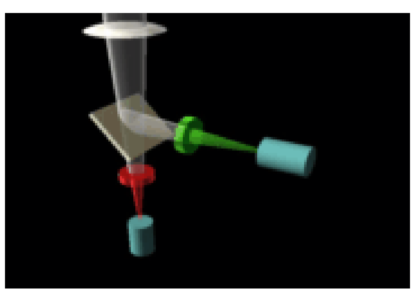
TOφCAM (**T**wo-Channel **O**ptical ***Ph***otometric ***I***maging **Cam**era) – pronounced "*toffee- cam*"

Potentially 160 TBytes of high quality data

Funded by Science Foundation Ireland

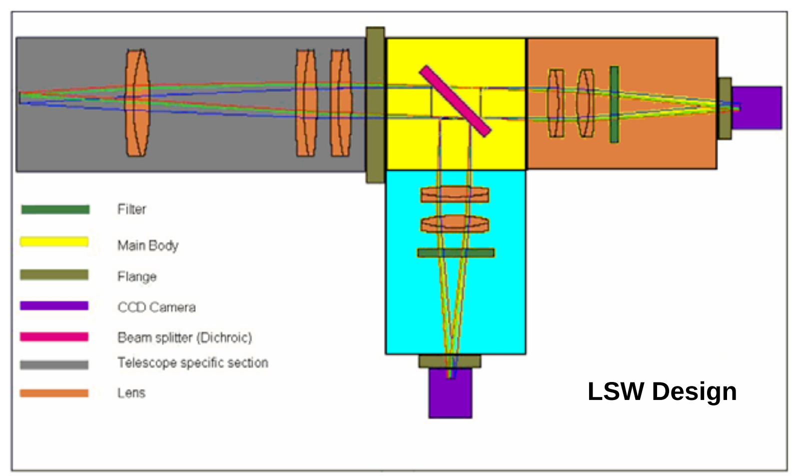
160 Nights Observation

- Greece – Kryoneri (1.2m)
- Greece – Aristarchos (2.3m)
- South Africa – Boyden (1.5m)



First light early 2007

Optical Layout



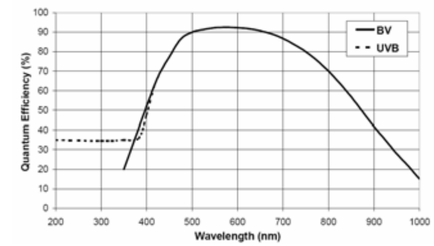
Mechanical Design

- Design and Fabrication - Mechanical Engineering Dept in CIT
- Design
  - Compact, lightweight, simple (no moving parts)
  - Rigid chassis
  - Optics fixed, except one changeable filter
  - Collimator optics fitted per telescope
  - Generally have all day to make changes - no need for quick release/easy access!!

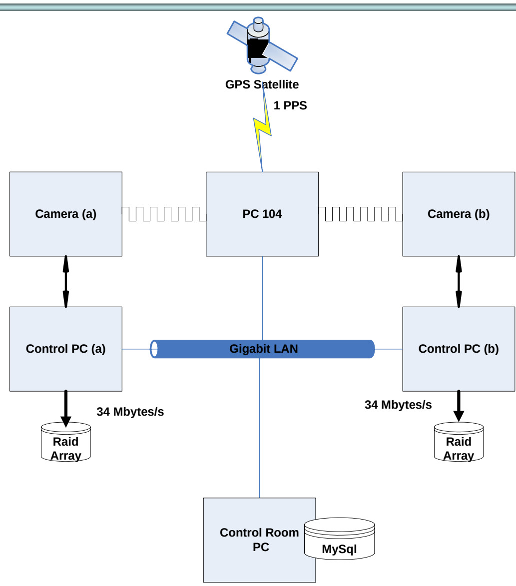
Detectors

- E2V CCD97-00 L3 sensors
- Back illuminated
- Frame Transfer
- Thermoelectrically cooled

Active Pixels	512 x 512
Pixel size (μm)	16 x 16
Image area (mm)	8.2 x 8.2
Well depth (e$^-$)	160,000
Readout Rate (MHz)	10
Frame Rate (frames per sec)	34
Read Noise (e$^-$)	< 1
Dark Current @ -85 °C (e$^-$/pix/sec)	0.001
Gain	1000
Peak QE (%)	90
Cooling Temperature (°C)	-100



Data Acquisition



- Timing
  - GPS
  - 1PPS
  - ms resolution
  - PC104 controlling triggering and logging of timestamps
- 2 camera control PCs
  - P4, 2 GB RAM
  - Raid 0 SATA HDs
  - 4 x 200 GB drives
  - Data stream to disk
  - Removable HDs
- Control PC (GUI)
  - TCP/IP over Ethernet communication
  - Remote access
- Live Photometry

Thoughts

<u>Reduction Methodologies</u>

Is there an optimum way?

<u>Intensive monitoring</u>

Access to guaranteed time
What type of equipment available?
Harmonising the results through calibration.

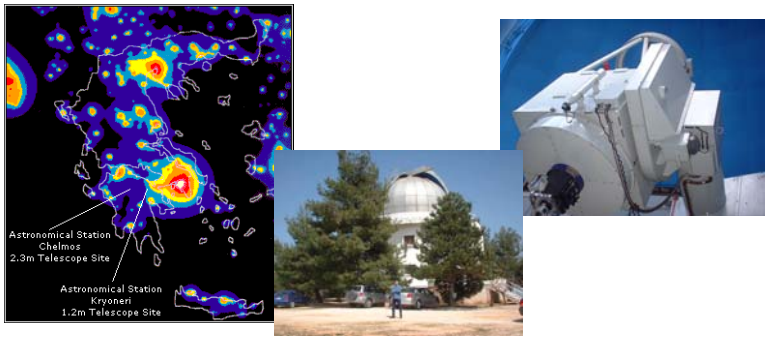
<u>Coordinated monitoring</u>

How do we decide upon targets?
Are flaring sources always best?

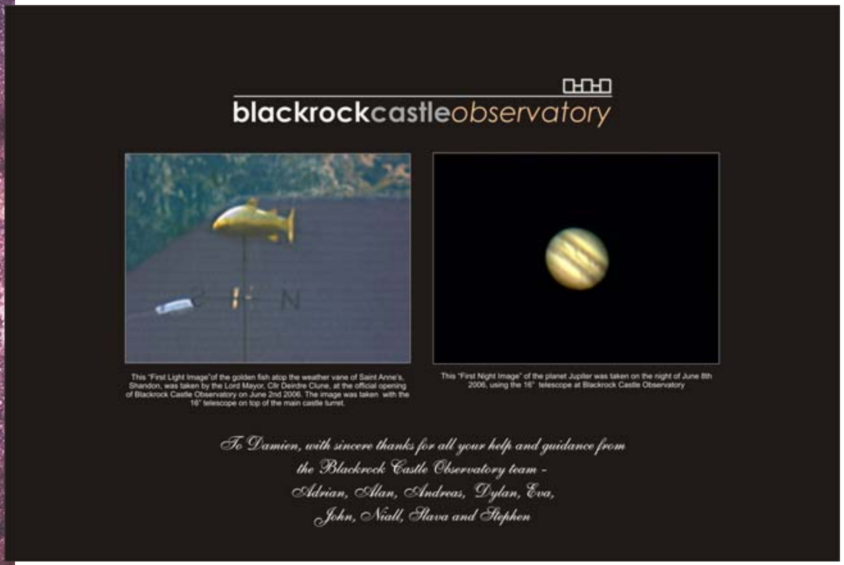
A few more thoughts

- Requirements of high precision photometry are somewhat at odds with those of optical photometry aimed at supporting a large multiwavelength campaign
- Community mostly interested in multiwavelength campaigns
- Need a network of telescopes as identical as possible (detectors, optical elements) with precision timing
- Long data trains
- We plan to use 2 EMCCDs with two identical filter sets to test how similarly we can determine the lightcurve of a source from two different locations

Kryoneri Telescope Project



- Agreement in place with Institute of Astronomy & Astrophysics, Athens
- Now have secured funding to robotise the 1.2m Kryoneri Telescope



Thankyou for your attention