Time Domain Survey from Antarctica – from Optical to Near Infrared

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On behalf of the Dome A Collaboration

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Dome A in 2008

China/Australia/USA
Kunlun Station
Jan 27, 2009
CSTAR: 2008—2011

- Aperture: 14.5 cm
- 4 independent telescopes
- 1kX1k interline transfer detector
- FoV: 4.5°X4.5°
- Fixed mount
CSTAR - Photometric quality of the CSTAR 2008 data set

The standard deviation (20 second or 30 second sampling; 158 day time scale) of each CSTAR light curve is plotted as a function of their median $i$-magnitudes. The solid orange line represents the trend of this distribution. Objects above 3 sigma threshold (the dashed orange line) are tagged as variable.

Wang, Songhu, et al. 2015
CSTAR – Light curves of a 4 binary stars

Yang, M. et al., 2015
δ Scuti star

Uninterrupted 4.5-d light curve (representing 3.5% of the entire data).

Folded light curve using $P = 0.2193\text{d}$; the photometric uncertainty is 1.5 mmag/bin.

Lingzhi Wang, Lucas Macri et al. 2011
Fig. 9.— Fourier spectrum of CSTAR \#n090586 derived using the Period04 program, based on data obtained during the first (top) and second (bottom) half of the 2010 season. Three significant peaks (at $f_i = 44.288$, 44.169, and 42.121 cycles d$^{-1}$) are detected with varying amplitudes, which exhibit significant changes (4–11σ) relative to the 2008 season. See text for details.

Fig. 10.— Light curve of CSTAR\#n057725, showing the slow reduction in Cepheid-like pulsation amplitude during the 2008 season has been replaced by a more complex variability in 2010. Eclipse-like events seem to be present at two distinct phases indicated with red and blue arrows, respectively.
CSTAR in g, clear, and r

Scintillation floor is $\sim 1.2$ mmag

Oelkers, R. et al. 2015
Small Telescopes Covering Wide Areas to Monitor Bright Stars in the Northern Hemisphere

1. Continuous Monitoring of
   - CSTAR – 14.5 cm, for Stars brighter than 12\textsuperscript{th} mag
   - AST3, ASTEP – 40-50cm for stars brighter than 16\textsuperscript{th} mag

2. Daily monitoring and follow up of
   - SNe
   - GRBs, Orphan GRBs
   - AGN
Small Telescopes Covering Wide Areas to Monitor Bright Stars in the Northern Hemisphere

- Related Sciences
  - ExoPlanet Transit/Microlensing
  - Stellar Structure
  - SN Discoveries/Observations - > Cosmology
  - AGNs/Black Holes
  - GRBs/Orphan GRBs
  - ...

Time Domain
Antarctic Survey Telescopes (AST3)

An Array of three 50cm Diameter

Supernovae and Exoplanets

Operational Mode

- Covers 1500 square degrees 3 times everyday SNe, AGN/QSO, Black Holes, GRB/Orphan GRB ...
- Covers 4.2 square degrees 3 times every minute Stars, Planets
- Covers 13 square degrees 3 times every minute
The Antarctica Survey Telescopes (AST3)

**AST3-1 (文)**
- 68cm diameter aperture
- Frame transfer CCD
- 5K X 10K pixels
- 1”/pixel
- Field of view ~ 4.3 sq deg
- i-band

**AST3-2 (武)**
- 68cm diameter aperture
- Frame transfer CCD
- 5K X 10K pixels
- 1”/pixel
- Field of view ~ 4.3 sq deg
- g-band, open

**AST3-3 (成), not yet installed**
- 68cm diameter aperture
- H2RG
- 2K X 2K pixels
- ~2”/pixel
- Field of view ~ 1.2 sq deg
- K-band

**CSTAR-1 (尧) and CSTAR2 (舜)**
- 14.5cm diameter aperture
- Interline frame transfer CCD
- 1K X 1K pixels
- ~ 20 sq deg FoV
- g- and i-band
Science Mode I
1. Survey operation
   • Rolling survey of ~ 1000 sq deg with cadence 0.25 - 0.5 days
   • Rolling survey of ~ 1000 sq deg with cadence of 5 days.
2. Scientific objectives
   • Supernovae within a day after explosion
   • Precision photometry of a wide area

Science Mode II
1. Survey operation
   • Rolling survey of ~ 20 sq deg on the galactic plane, cadence 10 sec – 60 sec
2. Scientific objectives
   • Exoplanets, asteroseismology
Fast Radio Burst
- Stellar flares
- Black hole collisions
- Lightning on exoplanets
- RRAIT – Rotating RAdio Transients
- Extraterrestrial communication

Lasts milliseconds; ~ 10,000 bursts/day over the entire sky; Might be the first detection of quantum gravity effect

Science Mode III
Targets only detectable for less than a few seconds

CSTAR Twin
AST3-1 and -2

The Antarctica Survey Telescopes (AST3)
Dome A in 2008

China/Australia/USA
Dome A in 2015
AST3 Status

- Commissioning started at 1 am, March 15, 2012
- Total observing time 746 hours till May 8, 2012
- 20% of the time used for engineering, most of which during the March period
- Only three nights lost due to reasons possibly related to bad weather
- Collected 28,535 images, about 3.3TB data till May 8, 2012
AST3 Status

- Installation of AST3-2 in 2014-1015 traverse
- Resumption of Science Operation starting from April 15, 2014
- Construction of AST3-3, optimized for optical and K-band started already
- Ast3-3 installation in Antarctica in 2017-1018 traverse
Diagnostic Images transmitted back through Iridium Openport
Preliminary Performance

• Sensitivity: $i=19.5$ (3 sigma) in 1 minute
• Image quality ~ FWHM~2''.0 (1''/pix, resolution limited by optics)
• Lowest relative photometric precision achieved so far ~ 0.2mmag
• Seeing estimated from image centroid motion at high speed (~kHz) readout ~ 0.2-1.5 arcsec
• no obvious clouds except for two nights
Sample Science for KISS
Kunlun Infrared Sky Survey

from the ARC LIEF proposal

- Supernovae & the Equation of State
- Reverberation Mapping and the Physics of AGN
- Gamma Ray Bursters (super-supernovae)
- Cosmic Near-Infrared Background
- Terminal phases of Red Giants (Miras)
- Dynamics and Variability in Star Formation
- Discovery of Exo-Planets (esp. Brown Dwarfs & Hot Jupiters)
Kunlun Dark Universe Survey
Telescopes (KDUST)

1. 2.5 meter aperture
2. ~0.12 arcsec pixel
3. 40K X 40K = 1.6G pixels
Intermediate Size Telescopes Covering Wide Areas for Cosmological Surveys

Typical Size of the most distant galaxies $\sim 0.5$ arcsec

Seeing limited Surveys at Dome A

1. Weak lensing, BAO
2. Deep Universe, but not so deep w/o NIR
3. Supernova Surveys
4. Exoplanets, Stars, ...
Sharper and Redder Images

Intermediate Size Telescopes Covering Wide Areas for Cosmological Surveys

Typical Size of the most distant galaxies ~ 0.5 arcsec

Seeing limited Surveys at Dome A in the NIR

1. Weak lensing, BAO
2. Deep Universe, approaching the epoch of re-ionization
3. Supernova Surveys, look for the first stars
4. Exoplanets, Stars, find an earth parallel
1. When and How did the universe made its first stars?
2. When and how did the universe made its chemical elements that are capable of producing life in the universe?
3. How did the universe made planets like the earth?
What are there?

- Olbers’ paradox
- Jim Peebles: In a Big Bang-created Universe there must have been a cosmic infrared background (CIB) – different from the cosmic microwave background – that can account for the formation and evolution of stars and galaxies
- Supernovae
- QSOs and ULIRGS
### KDUST Sensitivity

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda$ ((\mu)m)</th>
<th>$\lambda/\Delta\lambda$</th>
<th>FWHM (arcsec)</th>
<th>$m_{AB}$</th>
<th>$m_{Vega}$</th>
<th>$m_{AB}$ (arcsec(^{-2}))</th>
<th>$m_{Vega}$ (arcsec(^{-2}))</th>
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</thead>
<tbody>
<tr>
<td>$g$</td>
<td>0.47</td>
<td>3.4</td>
<td>0.35</td>
<td>27.6</td>
<td>27.6</td>
<td>27.1</td>
<td>27.1</td>
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<td>$r$</td>
<td>0.62</td>
<td>4.4</td>
<td>0.33</td>
<td>27.1</td>
<td>26.9</td>
<td>26.5</td>
<td>26.3</td>
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<tr>
<td>$i$</td>
<td>0.76</td>
<td>5.1</td>
<td>0.32</td>
<td>26.6</td>
<td>26.2</td>
<td>26.0</td>
<td>25.6</td>
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<tr>
<td>$z$</td>
<td>0.91</td>
<td>6.5</td>
<td>0.31</td>
<td>25.8</td>
<td>25.3</td>
<td>25.1</td>
<td>24.6</td>
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<tr>
<td>$Y$</td>
<td>1.04</td>
<td>5.1</td>
<td>0.30</td>
<td>25.3</td>
<td>24.7</td>
<td>24.6</td>
<td>24.0</td>
</tr>
<tr>
<td>$J$</td>
<td>1.21</td>
<td>4.6</td>
<td>0.30</td>
<td>25.0</td>
<td>24.1</td>
<td>24.3</td>
<td>23.4</td>
</tr>
<tr>
<td>$H$</td>
<td>1.65</td>
<td>5.7</td>
<td>0.29</td>
<td>24.4</td>
<td>23.0</td>
<td>23.6</td>
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<td>$K_d$</td>
<td>2.40</td>
<td>10</td>
<td>0.32</td>
<td>25.3</td>
<td>23.3</td>
<td>24.7</td>
<td>22.7</td>
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<tr>
<td>$L$</td>
<td>3.76</td>
<td>5.8</td>
<td>0.40</td>
<td>21.2</td>
<td>18.3</td>
<td>20.8</td>
<td>17.9</td>
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<td>$M$</td>
<td>4.66</td>
<td>19</td>
<td>0.46</td>
<td>19.6</td>
<td>16.2</td>
<td>19.4</td>
<td>16.0</td>
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<tr>
<td>$N'$</td>
<td>11.5</td>
<td>11</td>
<td>1.05</td>
<td>16.3</td>
<td>11.2</td>
<td>17.0</td>
<td>11.9</td>
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<td>$Q_N$</td>
<td>20.1</td>
<td>20</td>
<td>1.80</td>
<td>14.6</td>
<td>8.1</td>
<td>15.8</td>
<td>9.3</td>
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</tbody>
</table>
### VISTA survey observing strategies

<table>
<thead>
<tr>
<th>Survey</th>
<th>Area (deg$^2$)</th>
<th>Filters and Depth Measure (mag (10σ, AB))</th>
<th>Depth (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-VISTA</td>
<td>0.73 (ultra-deep)</td>
<td>5σ, AB</td>
<td>Y=26.7, J=26.6, H=26.1, $K_s$=25.6, NB=26.0</td>
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<tr>
<td>VIKING</td>
<td>1500</td>
<td>5σ, AB</td>
<td>Z=23.1, Y=22.3, J=22.1, H=21.5, $K_s$=21.2</td>
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<tr>
<td>VMC</td>
<td>184</td>
<td>10σ, Vega</td>
<td>Y=21.9, J=21.4, $K_s$=20.3</td>
</tr>
<tr>
<td>VVV</td>
<td>520</td>
<td>5σ, Vega</td>
<td>Z=21.9, Y=21.2, J=20.2, H=18.2, $K_s$=18.1</td>
</tr>
<tr>
<td>VHS</td>
<td>20 000</td>
<td>5σ, AB</td>
<td>Y=21.2, J=21.2, H=20.6, $K_s$=20.0</td>
</tr>
<tr>
<td>VIDEO</td>
<td>12</td>
<td>5σ, AB</td>
<td>Z=25.7, Y=24.6, J=24.5, H=24.0, $K_s$=23.5</td>
</tr>
</tbody>
</table>

**KDUST:**

25.3 mag in 1 hour
zETA Science Objectives Are Achievable with KDUST Telescope

Three NIR survey data products:

1. Time domain survey to $K = 25^{th}.3$ mag, 3-4 times a day over a total of 3-4 deg$^2$ field
2. 1000 deg$^2$/year to $K = 25^{th}.3$ mag
3. Stacked deep field of 3-4 deg$^2$ to $K = 29^{th}$ mag

- The total amount of astronomically dark time at Dome A is 2606 hours/year (Zou et al. 2010)
- Each year about 1380 hours will be devoted to time domain survey
- Each year about 1000 hours will be devoted to wide area survey
zETA with KDUST

• The KDUST K-band survey will produce
  – 3-4 sq deg deep fields to K = 29, intensive time-domain coverage (3-4 times a day!!!). ~ 1 PISNe/year.
  – 1000 sq deg to about 25.3 mag

• For comparison, the Ultra-VISTA survey is 5σ to a depth of 25.6 mag (AB) over a field of view of 0.73 deg².
Observations

NIR light curves for five Pop III SNe at 2.0 μm at $z = 15$ (solid) and $z = 20$ (dotted). The horizontal lines are the detection limit for WFIRST (27 mag, AB) and JWST (32 mag, AB). The limiting magnitude of the zETA deep field is 29 mag (AB). (From Whalen et al. 2013, ApJ, 762, 6).
SLSNe – Super-Luminous SNe
SLSNe II – Hydrogen Rich
Detectability of SLSNe

The upper and lower curves are blackbody fits to the observed photometry. The temperature and radius evolve with time.
Two SLSNe at $z \sim 1.5$

These two high-$z$ SNe are intrinsically dimmer than SN 2008es.
Two SLSNe at $z \sim 2-4$

These two SNe have about the same intrinsic brightness Compared with SN2008es
A deep Y-band survey will find the brightest SLSNe at $z \sim 6$; zETA will find SNe out to $z \sim 20$!
A deep Y-band survey with DES will find the brightest SLSNe at $z \sim 6$;

SN 2008es at $z = 6$, $z = 10$, $z = 20$

zETA will detect $z \sim 10$ SLSNe at 5 $\sigma$ level in its one hour exposures.

zETA will find SLSNe out to $z \sim 20$!
Observations

NIR light curves for five Pop III SNe at 2.0 μm at z = 15 (solid) and z = 20 (dotted). The horizontal lines are the detection limit for WFIRST (27 mag, AB) and JWST (32 mag, AB). The limiting magnitude of the zETA deep field is 29 mag (AB). (From Whalen et al. 2013, ApJ, 762, 6).

Time dilation: at z = 20, 17 days in the rest frame translates into one year in the observer’s frame, i.e. it takes 20 years to acquire a full year’s light curve of a z ~ 20 supernova.

We need to run a multi-year program to find a z ~ 20 supernova, a task that cannot be easily fulfilled by any space mission.
Future Perspectives

- AST3 and time domain Optical/NIR survey
- LSST can help, by not being able to detect $z \sim 10 - 20$ targets
- GMT/E-ELT/TMT/JWST can be useful for follow up observations once a $z \sim 10 - 20$ object is found
- EUCLID/WFIRST can probe $z \sim 10$, but not $z \sim 20$
4. Summary

With the excellent observing conditions at Dome A, we aim to explore some of the most fundamental questions of humanity, namely

– When and How did the universe made its first stars?
– When and how did the universe made its chemical elements that are capable of producing life in the universe?
– How did the universe made its planets like the earth?