

An Antarctic, Full-sky, High-speed, Imaging Array for Optical Transients

Donald G. York¹

Abstract. Many problems in time domain astronomy are best approached with continuous, high frequency (< 1 minute) observations over a large area of the sky, because event rates are generally less than 0.01 detections per sq. degree in a year. For GRBs and the earliest stages of SNe, follow-up spectroscopy, multiband photometry and polarization measurements need to be triggered in seconds or minutes. Plateau sites in Antarctica are optimal for a new survey, Xian (eXtreme Imaging Antarctic Network), for which the scientific motivation is presented.

1. Introduction

Surveys for optical, transient objects in the sky have a long history (Zwicky 1938, Schaefer *et al.* 1984, Rykoff *et al.* 2005, Becker *et al.* 2004, Frieman *et al.* 2008). We discuss here a transient survey with 10-20 second time resolution including thousands of square degrees of sky. Located at Dome C and/or Dome A, the survey would provide uninterrupted observations, 24 hours each day, for periods of at least three months of each year.

2. Description of the system

The concept of Xian is described by York *et al.* 2006. It consists of 400, 50-cm diameter Schmidt telescopes, each with a 20-degree, CCD-filled focal plane. An on-site telescope for follow-up is needed. We assume an image point spread function of two arcsec (Fossat 2008, York *et al.* 2006) in filterless operation; a scale of 1 arcsecond per pixel; and a sky-limited magnitude in dark skies of 20th V magnitude in 20 seconds, 23rd magnitude for co-addition of one hour of data and 25th for one day of co-added data. The system is operated in drift-scan mode (see Djorgovski *et al.* 2008). The integration time is fixed by a high density of read-out pre-amplifiers on the CCDs (~150 rows apart). The baseline integration is 10 seconds on the equator and 10/cos δ seconds at lower declinations. The entire system operates without moving parts. The CCD Dewars are to operate at ambient temperature in winter, but can be cooled for pre-delivery testing and for summer testing at the site. At Dome C in Antarctica, the skies are expected to be effectively over 90% clear (with techniques of Ivezić *et al.* 2007) and the wind speeds

¹ 5640 So. Ellis Avenue, AAC002, Chicago, IL, 60637.

are modest (Fossat 2008). The moon does not produce a sky brightness above 18th magnitude per square arcsecond (A. Moore, priv. comm.). Both Dome C and Dome A can be considered for parts of the array (Tothill *et al.* 2008).

On-site software is used to compare the readout of each CCD line (~100ms line times) pixel by pixel with a dynamic template (to V=25) (Djorkovski *et al.* 2008), to trigger on new point sources that rise above some threshold in brightness. Subsequent, stationary detections indicate a persistent event that will trigger (low bandwidth) international alerts, and bring the local, follow-up telescope into action. (An effective strategy for follow-up instrumentation is presented by Gomboc *et al.* 2005, though we would add an echelle.) False positives should be very low in number, as explained below. Data at the highest time resolution can be compressed, after on-line examination, to one hour, three hour, 10 hour, etc. co-adds, and those can be compared to search for longer transients. The computers needed for the array amount to less than one powerful workstation per telescope. A telescope/computer module that fails can be totally replaced.

3. Performance metrics for transient detection systems

The total sky coverage of a system in one year of observing is h (deg.sq.-year). The metric is specified for an optimal time scale (τ) and a limiting magnitude, V_{lim} : $h = n \times M \times \Omega \times N \times \alpha \times \beta \times \epsilon$ (see for instance, Becker, *et al.* 2004). In the equation, n is the fraction of night hours available; M is the fraction of moon free hours; Ω is the intrinsic field of view of the survey telescope (or of each, in an array); N is the number of fields covered in the timescale being searched; α is the fraction of observing hours that are clear; β is the fraction of nights that have appropriate seeing; and ϵ is an efficiency factor (system dependent.)

We estimate that, for SDSS-I (York *et al.* 2000), SDSS-SNe search (Frieman *et al.* 2008), Xian (York *et al.* 2006) and SWIFT (Gehrels *et al.* 2004), the metrics (τ , h) are (100sec, 0.02), 3×10^5 sec, 22), (10^3 - 10^6 sec, 1600) and ($<10^3$ sec, 8000), respectively.

The quantities τ , V_{lim} and h must be traded off for any system. We find that (τ , V_{lim} , h) for Pi of the Sky (Burd *et al.* 2005); ROTSE (Rykoff *et al.* 2005); SDSS-SNe; a single Xian Schmidt module at +30 degrees declination; Xian; and LSST (Tyson 2002) are (1000 sec, 12, 600), (1800 sec, 18, 1.7), (10^6 sec, 22, 24), (10^6 sec, 23, 72), (20 to 10^6 sec, 20 to 25, 1600), and (10^6 sec, 26, 2240). A single Schmidt or LSST repurposed solely for $\tau < 1000$ sec has $h < 1$.

The number of objects observed in a survey in one year (η), given Φ , the number of objects per year of some class, is $\eta = h \times \Phi$. One object per day over the entire sky corresponds to $\Phi = 0.01$. For Type Ia SNe (Frieman *et al.* 2008), Type Ib/c SNe, Type II SNe (Mannucci *et al.* 2005) and AGN (Sesar *et al.* 2007), $\tau = 1$ hr and $V_{lim} = 23$, values of (Φ, η) are, respectively, (4.5, 6800), (0.02, 32), (0.2, 320), and (3600, 5 x

10^6). For short-term transients discussed later, Φ and η for Xian are listed in Table 1. Evidently, except for orphan afterglows, AGN and Type Ia SNe, significant values of η are not feasible without very large arrays.

In past transient surveys, false positives were more frequent by over a factor of 100 for all sources in Table 1 except the orphan afterglows. The triads (τ , Φ , V_{lim}) for cataclysmic variables (Rykoﬀ *et al.* 2005, Rau *et al.* 2007); red dwarf flare stars (Kulkarni and Rau 2006, S. Hawley, priv. comm.); asteroids, not previously catalogued, for ROTSE (C. Akerlof, priv. comm.); asteroids, not previously catalogued, for SDSS-SNe (R. Kessler, priv. comm.); and radiation hits (assumed to be 1/cm²/sec) are (1000 sec, 1, 19), (1000 sec, 10, 23), (1800 sec, 10^3 , 17.5), (10^5 sec, 10^6 , 22), and (<1 sec, 10^8 , --), respectively. Xian uniquely senses all of these false positives, by the use of line-by-line comparisons at CCD readout and by the use of a dynamical template (largely for asteroids).

Table 1: Occurrence rate of selected transients with Xian.

Object	τ (sec)	Φ	V limit	η	Reference
GRB	2-200	0.02	-----	(44)	Fenimore 1993
GRB afterglows	10^2 - 10^3	0.01	23	16	Lamb <i>et al.</i> 2004
Orphan afterglows	10^3 - 10^5	>2	23	>3200*	Zou <i>et al.</i> 2007 Rau <i>et al.</i> 2006
Blue flash SNe II	600	0.04	21.5 (z=0.1)	64	Blinnikov 1998 Mannucci <i>et al.</i> 2005
QSO/SNe lenses	10^4 - 10^5	0.01	22	16	Bolton & Burles 2003 Oguri <i>et al.</i> 2008
AM CVn	600	10^{-3}	19	2	Anderson <i>et al.</i> 2005
Planet eclipses	3600	0.01:	13	16	
Planet lenses	1000	0.001 -0.01*	19	16	Beaulieu <i>et al.</i> 2006 Han 2008

** The first number excludes the bulge, the second includes it.

4. Science

4.1 Supernovae

The specifications for Xian follow from the need to understand supernovae. The details of supernovae explosions are still a mystery because of the variety of mechanisms that may be involved, particularly in hypernovae and Type Ia SNe, and environmental issues. There is the possibility, on the one hand, that dust, formed in the rapid expansion, may affect the observations (Wang 2005). On the other hand, there may be additional bodies in the proximity of the SNe that may be affected

by the blast wave and cause extensions of the light curve. High frequency variability observations may shed light on the detailed physics of the explosions. For Type Ic supernovae, there is a tie-in with gamma ray bursts (GRBs) (Stanek *et al.* 2003), which appear a few days after some GRBs (further discussed below). For Type II SNe, the crossing time is tens of minutes and the blast wave may be observed at the surface, creating a precursor event and allowing the light curve to be followed over the earliest hours of the SNe. For Type I SNe, we really have little idea of what the first few minutes might look like, but early activity may be observable in the brightest objects.

The apparent luminosity of GRBs is so high that they must be beamed, but there are limits consistent with relativistic plasma being unassociated with most SNe (Gal-Yam *et al.* 2006). On the other hand, the jet picture for the rare Type Ic/GRBs (Lamb *et al.* 2005) must be only a first approximation, because the optical and X ray afterglows do not behave in a purely geometrical way (Panaitescu *et al.* 2006). It is not clear why the afterglows are so extended (up to 30 hours, Gomboc *et al.* 2005) and have structure. Some are not visible in the optical (Gomboc *et al.* 2005, Oates *et al.* 2006), perhaps because of dust in or near the object.

A persistent theme of the GRB data is that either there is material exterior to the original source, interacting with the jet, or there is something that keeps the central engine going for an extended period, such as infall after the burst. The short, hard bursts are defined as being < 2 sec in duration, but Norris and Bonnell 2006 found a one minute tail when many BATSE short bursts were summed. A strong test of the jet paradigm can be made if off-axis afterglows (orphans) can be seen. For current models, the predicted numbers are comfortably high (Table 1) for confirmation, but sampling on time scale of hours is necessary to safely define the light curves.

There are numerous theories that have been invoked to explain the details of these objects, but the observational situation needs to be better defined. Ground based detection of the GRB afterglows, without the GRB trigger, will allow precursors to be identified (Cenko *et al.* 2006) and the obtaining of extensive follow-up observations, to explore the presence of dust in the earliest phases, to measure polarization while the source is very bright and to obtain spectra throughout the event. Simultaneous optical, IR, gamma ray and X ray observations will be available while SWIFT is alive (Gehrels *et al.* 2004) and, in gamma rays for sometime to come, with GLAST (von Kienlin *et al.* 2004). A long-term hope is that optical and gamma ray transients will be found coincident with neutrino bursts (Razzague *et al.* 2004) or gravity wave signals (Abbott *et al.* 2006). This may need to be done by co-adding signals at locations of the optical and gamma ray bursts.

4.2 Intergalactic medium and cosmology

A transient detector such as Xian will make major contributions to the determination of cosmological constants and the probing of the high z Universe. The mean redshift of the GRBs is 2.8 (Jakobsson *et al.* 2006) and they may be observable at $z > 6$ (Lamb and Reichert 2000). Xu *et al.* 2005 have recently reviewed the possibilities of using GRBs as standard candles to determine the geometry of space at high z . The redshifts can be obtained from absorption lines local to the GRB (Prochaska *et al.* 2006) or by spectroscopy (Bloom *et al.* 2006) of the GRB host galaxy, once the afterglow fades.

The absorption lines can be used to analyze the environment of the GRB (Prochaska *et al.* 2006) and the abundances thereof. In some cases, it has been surmised that these lines arise in the pre-burst ejecta of a Wolf Rayet star (Klose *et al.* 2004). In addition, intergalactic absorption at lower redshifts will be seen, as in QSOs. The GRBs allow the probing of high- z IGM abundances that will complement observations in the few high z QSOs. The observations require high spectral resolution, very early (seconds) in the burst, hence on on-site, follow-up capability, 24 hours a day.

The use of variable multiple objects of lensed QSOs by foreground galaxies (Kundic *et al.* 1997), to determine H_0 , will be possible. Peculiar cases exist (Keeton *et al.* 2007), but a rationale for dealing with them is possible. Supernovae will be multiply lensed by cluster potential wells, complementary to determination of H_0 from QSOs (Bolton and Burles 2003). The timescales are months to years but continuous tracking is crucial to see the flux changes in one image of the lens mirrored in the other. Once the variations are found, the objects can be monitored from other observatories.

The number of lenses over the sky is a measure of the amount of dark energy in the Universe (Oguri *et al.* 2008). The use of standard Type Ia supernovae to determine the dark energy content is well known (Clocchiatti *et al.* 2006). These objects will be seen within one day of the explosions for thousands of objects each year and light curves of one hour resolution in white light will be available, to bridge gaps in the follow-up observations that should generally occur off site.

4.3 Variable stars

Cataclysmic variables (CVs: Rau *et al.* 2007) and dwarf flare stars (Kulkarni and Rau, 2006) provide the largest contamination sample in a survey of extragalactic transients: their systematic identification will make the extragalactic transient survey more effective and will qualitatively change our understanding of the CVs. Cataclysmic variables consist of compact objects accreting mass from lower mass companions. The periods range from 10 minutes to hundreds of days. In a transient survey to $> 23^{\text{rd}}$ magnitude over a day, dwarf novae will be the most frequent false positives (duration 3-5 days, periods of 40 days, burst magnitude ~ 5 magnitudes). The proposed survey should find virtually all of these in the Galaxy, out of the disk, and they

can be seen in their quiescent state in a $V_{\text{lim}} = 25$ template made with the Xian survey itself (in one day).

There are numerous manifestations of CVs, scientifically interesting because of the various mechanisms at work in their formation and evolution: mass transfer of deep layers of the secondary, magnetic braking, and gravitational radiation, the latter most manifest in the rare AM CVn stars (Anderson *et al.* 2005), likely to be seen by LIGO and candidates to become Type Ia SNe. A transient survey that is complete would allow a tie-in between a well-defined CV sample and surveys with strong selection effects but of a form that reveals the physics of selected objects in great detail (Szkody *et al.* 2006).

Dwarf flare stars (M stars that emit bursts of UV radiation) will similarly be eliminated by false positives. Since the flares are blue, they will not cause such a large problem for Xian (filterless) as for surveys in blue filters (Becker *et al.* 2004, Kulkarni and Rau, 2006). A large catalogue of such stars will, however, result. They can be used to understand the magnetic fields in late M stars and to understand the habitable zones for planets around such stars. Planets may be easier to find than in hotter main sequence stars, but the lower quiescent optical/IR energy and the flare impact on proximate planets may severely limit the life forms that can exist in such systems.

Asterioseismology to probe the stellar interiors of stars across the HR diagram will be possible for objects with periods of minutes to hours to days that cannot be done well where the day/night cycle or clouds interrupt observations (Zima, *et al.* 2002, Winget 1998, Kanaan *et al.* 2005, Kaye *et al.* 1999, Saio *et al.* 2006). Irregular variables from pre-supernova stars to forming stellar accretion disks will also obtain unprecedented coverage because of their erratic nature and the continuous nature of the data streams.

Finally, low mass planets can be observed in lensing situations (Beaulieu *et al.* 2006) and in eclipsing situations. The former case involves using machos for which the foreground star has planet(s). Most studies are concentrating on the bulge of the Galaxy since the number of Galactic objects outside the bulge is small (Han 2008, see Table 1). Eclipsing planets can be studied by the attenuation of the stellar light by a transiting planet on time scales of hours, for the brightest objects that can be observed without saturating the CCDs. The eclipsing systems are critical for the study of planetary atmospheres.

5. Conclusion

Searches for selected transient objects benefit from a fast, full-sky transient array at Dome C and/or Dome A, with time scales of > 20 seconds. The long, continuous night and immediate follow-up with an on-site telescope are crucial for studies that will lead to a more complete observational understanding of the early stages of supernovae, of the GRB phenomenon and of cosmological parameters. Variable star

studies will greatly benefit from the same survey. The time domain of Xian, is highly complementary to LSST, PanSTARRS and Skymapper.

6. Acknowledgements

In addition to the co-authors of York et al. 2006, Rick Kessler (U. Chicago), L. Feng, J. Yang, J. Yan, Z. Zhu (PMO, Nanjing), Z. Jiang (NAOC), Daniel Luong-Van (UNSW), Z. Shang (Tianjing Normal University), are now associated with the project and are thanked for their input. Josh Frieman, Hsiao-Wen Chen, Andy Puckett, Dean Townsley (U. Chicago), Suzanne Hawley (Univ. of Washington), Shude Mao (U. Manchester), and Brian Wilhite (UIUC) provided important input for the science discussion.

7. References

- Abbott, B., Abbott, R., Adhikari, R. 2006, PhRvD, 73, 2001.
Anderson, S. F., Haggard, D., Homer, L. et al. 2005, AJ, 130, 2230.
Beaulieu, J.-P., Bennett, D. P. et al. 2006, Nature, 439, 437.
Blinnikov, S. I., Eastman, R. et al. 1998, Ap, 496, 454.
Becker, A. C., Wittman, D. M. et al. 2004, ApJ, 611, 418.
Bloom, J. S., Prochaska, J. X., Pooley, D. et al. 2006, ApJ, 638, 354.
Bolton, A. S. and Burles, S. 2003, ApJ, 592, 17.
Burd, A., Cwiok, M., Czyrkowski, H. et al. 2005, NewA, 10, 409.
Cenko, S. B., Kasliwal, M., Harrison, F. A. 2006, ApJ, 652, 490.
Clocchiatti, A., Schmidt, B. P. et al. 2006, ApJ, 642, 1.
Djorgovski, S. G., Baltay, C. et al. 2008, arXiv:0801.3005.
Fenimore, E. E., Epstein, R. I., Ho, C. et al. 1993, Nature, 366, 40.
Fossat, E. 2008, this volume.
Frieman, J. A., Bassett, B., Becker, A. et al. 2008, AJ, 135, 338.
Gal-Yam, A., Ofek, E. O., Poznanski, D. 2006, ApJ, 639, 331.
Gehrels, N., Chincarini, G., Giommi, P. 2004, ApJ, 611, 1005.
Gomboc, A., Guidorzi, C., Mundell, C. G. et al. 2005, arXiv/0612762.
Han, Cheongho 2008, ApJ, in press.
Ivezic, Z., Smith, J. A., Miknaitis, G. et al. 2007, AJ, 134, 973.
Jakobsson, P., Levan, A. et al. 2006, A&A, 447, 897.
Kanaan, A., Nitta, A., Winget, D. E. 2005, A&A, 432, 219.
Kaye, A. B., Handler, G. et al. 1999, PASP, 111, 840, 1999
Keeton, C. R., Burles, S., Schechter, P. L. et al. 2006, ApJ, 639, 1.
Klose, S., Greiner, J., Rau, A. et al. 2004, AJ, 128, 1942.
Kulkarni, S. R. and Rau, A. 2006, ApJL, 644, 63.
Kundic, T., Turner, E. L., Colley, W. N., et al. 1997, ApJ, 482, 75.
Lamb, D. Q. and Reichart, D. E. 2000, ApJ, 536, 1.
Lamb, D. Q., Ricker, G. R., Atteia, J.-L. et al. 2004, NewAR, 48, 423
Lamb, D. Q., Donaghy, T. Q., and Graziani, C. 2005, ApJ, 620, 355.
Mannucci, F., Della Valle, M., Panagia, N. et al. 2005, A&A, 433, 807.
Norris, J. P. and Bonnell, J. T. 2006, ApJ, 643, 266.
Oates, S. R., Mundell, C. G. et al. 2006, MNRAS, 372, 327.

Oguri, M., Inada, N., Strauss, M. A. *et al.* 2008, AJ, 135, 512.
Panaitescu, A., Meszaros, P. *et al.* 2006, MNRAS, 369, 2059.
Prochaska, J. X., Chen, H.-W., and Bloom, J. S. 2006, ApJ, 648, 95.
Rau, A., Greiner, J. and Schwarz, R. 2006, A&A, 449, 79.
Rau, A., Schwarz, R., Kulkarni, S. R. *et al.* 2007, ApJ, 664, 474.
Razzaque, S., Meszaros, P. and Waxman, E. 2004 PhRvL, 93, 181101.
Rykoff, E. S., Aharonian, F., *et al.* 2005, ApJ, 631, 1032.
Saio, H., Kuschnig, R., *et al.* 2006, ApJ, 650, 1111.
Schaefer, B. E., Vanderspek, R., *et al.* 1984, ApJ, 283, 887.
Sesar, B., Ivezić, Z., Lupton, R. *et al.* 2007, AJ, 134, 2236.
Stanek, K. Z., Matheson, T. *et al.* 2003, ApJ, 591, L17.
Szkody, P., Henden, A., Agueros, M. *et al.* 2006, AJ, 131, 973.
Tohill, N. F. H., Kulesa, C. A., *et al.* 2008, this volume.
Tyson, J. A. 2002. SPIE, 4846, 10.
von Kienlin, A., Meegan, C. A. *et al.* 2004, SPIE, 5488, 763.
Wang, L. 2005, ApJ, 635, L33.
Winget, D. E. 1998, JPCM, 10, 11247.
Xu, D., Dai, Z. G., and Liang, E. W. 2005, ApJ, 633, 603.
York, D. G., Wang, L., Cui, X. *et al.* 2006, SPIE, 6267, 46.
York, D. G., Adelman, J. *et al.* 2000, AJ, 120, 1579.
Zima, W., Breger, M., Bischof, K. *et al.* 2002, ASPC, 259, 598.
Zou, Y. C., Wu, X. F. and Dai, Z. G. 2007. A&A, 461, 115.
Zwicky, F. 1938, PASP, 50, 215.