A large array of telescopes in Antarctica with all-sky imaging every 5 seconds

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ABSTRACT

We describe a large-angle survey for fast, optical transients: gamma ray bursts (GRBs), supernovae (SNe), lensed and transiting planets, AGNs and serendipitously found objects. The principal science goals are to obtain light curves for all transients and to obtain redshifts of GRBs and orphan afterglows. The array is called Xian. In conjunction with the gamma-ray satellites, ECLAIRs/SVOM and GLAST, the data will be used to study sources from z=0.1 to >6. The telescope array has 400 Schmidt telescopes, each with ~20 sq. degree focal planes and apertures of ~0.5 meters. The passively cooled, multiple CCD arrays have a total of 16000x16000 pixels, up to 13 readout channels per 1K x 4K CCD and work in TDI mode. The system provides continuous coverage of the circumpolar sky, from the Antarctic plateau, every few seconds. Images averaged over longer time intervals allow searches for the host galaxies of the detected transients, as well as for fainter, longer timescale transients. Complete, data at high time resolution are only stored for selected objects. The telescopes are fixed and use a single filter: there are few (or no) moving parts. Expected detection rates are 0.3 GRBs afterglows per day, >100 orphan afterglows per day and >0.1 blue flashes per day from Type II or Type Ib/c supernovae. On-site computers compare successive images and trigger follow-up observations of selected objects with a co-sited, well-instrumented telescope (optical, IR; spectroscopy, photometry, polarimetry), for rapid follow-up of transients. Precursor arrays with 20-100 square degrees are planned for the purpose of developing trigger software, testing observing strategies and deriving good cost estimates for a full set of telescope units.

Key words: Time domain astronomy; supernovae; gamma-ray bursts; Antarctica; telescopes; astronomical transients.

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1. Introduction

Transient astrophysical sources have been central to astronomical research for years. Examples include supernovae; standard candle, regular variables (RR Lyr stars, Cepheid variables); and irregular variables such as cataclysmic variable stars. Such objects have traditionally been found using patrol surveys or serendipitously. In the last 30 years, transient gamma-ray bursts (GRBs) have been found[1]. A number of gamma-ray satellites have been involved in the discovery of about 4500 GRBs: KONUS[2], BATSE[3]; BeppoSAX[4,5], HETE-2[6], INTEGRAL[7]; and SWIFT[8] and others. Flare stars within the Galaxy have been known for years, of course. After many years of searching[9, 10], follow-up observations of gamma-ray bursts (GRBs) finally led to the discovery of brief optical transients that were extragalactic. To our knowledge, there are no verified, extragalactic, optical transients (that is, transients with no quiescent source detected before or after a burst of duration <30 hours) found except by follow-up of GRB transients. Extragalactic X-ray transients also occur, which are thought to be variants of the gamma-ray burst phenomenon[11]

Short optical transients are of potentially great importance in studies of astrophysical objects, in particular, for stars in their last stages of evolution, but having to find them using follow-up of gamma ray bursts with ground based telescopes leads to great inefficiencies. There are only a few hours in which to get data before the optical afterglow of a GRB fades, weather is problematic, the correct instruments may not be available, etc. There are some fairly complete, published, optical light curves for GRB afterglows (for example, GRB021211[12] and GRB030329[13], but usually, only a few data points in a few filters are obtained. The situation has improved significantly with the launch of the SWIFT satellite which can slew a UV-optical camera (UVOT) onto a gamma-ray burst, automatically and provide routine follow-up for a few days[14]. Several fast-acquisition, ground based telescopes, such as PROMPT[15,] RAPTOR[16], and ROTSE III[17] stand ready to follow up the Gamma-Ray Burst Circular Network (GCN) notices[18]. However, a complete description of the nature of gamma-ray burst sources will involve a full data set for thousands of objects, and their characterization at late times when the objects are faint. (About 4500 GRBs have been detected, but only a few have been localized to better than five arcminutes (350), and of these, 135 have been localized by SWIFT to within 5 arcseconds, good enough to find the optical counterpart in a straight forward manner.) The collection of the needed dataset cannot occur using available tools: a dedicated instrument must be developed.

We explore here a concept for a ground-based detection system that can work independently of gamma-ray satellites and provide UVOT-like follow-up of greater scope, an essential tool in the timeframe of GLAST[19], a new gamma-ray satellite which has no counterpart to UVOT or XRT (an X-Ray imager), and hence, which cannot localize the bursts for ground-based follow-up. The proposed system, located on the Antarctic plateau, can detect bursts that are 20th magnitude in V or R over 5-10 seconds (thus possibly picking up 25-50% of GRBs occurring at the same time in the same part of the sky). Co-addition of the short exposures can be used to build up deeper images that can be used for searches of longer scale transients (such as conventional supernovae) and to provide detection of the host galaxies after the GRB afterglow has faded. Such a system can be used for detecting other short, optical transients, such as flashes from supernovae and cataclysmic variables.

We provide a brief section on background (section 2), then describe the scientific motivation for the optical transient array (section 3). The project elements (requirements, collaboration, site, telescopes, detectors, triggering on bursts, elimination of false positives and an on-site telescope for follow-up) are described in section 4, and the philosophy of evolving the final design in section 5. Section 6 gives figures of merit for comparison of several related projects. The conclusions are given in Section 7.

2. Background

Supernovae have been observed throughout the history of mankind[20].. The discovery of S And in 1885[21] played a role in the gradual acceptance of the idea that galaxies are distributed throughout a vast space of the Universe, not confined only to our Galaxy[22]. Zwicky boldly surveyed the sky for supernovae with an 18-inch Schmidt at Mt. Palomar[23] and established that supernovae are normal events in the Universe. We now associate them with dying stars of high mass (Type II, Type Ib, Type Ic) or low mass (Type Ia). Type Ia supernovae, thought to be caused by Roche lobe overflow of material from a red giant to a white dwarf that is just below critical mass (the Chandrashekar mass) (but possibly having additional causes), are used as standard candles to measure the expansion rate of the Universe and were the cornerstone of the recent discovery of evidence for dark energy in the Universe[24, 25,26].

Gamma-ray bursts were discovered, serendipitously, using military satellites[1]. A series of gamma-ray satellites, noted earlier, have been used to characterize these bursts. The total number of bursts detected by these instruments approaches 4500, comparable to the number of detected optical supernovae. There are at least two types[27]: long bursts (lifetimes of typically 30 seconds), now known to be mostly located in high redshift galaxies[28] (i.e., cosmological) and short, hard bursts, with timescales of <2 seconds (observer frame), recently shown to be, in a few cases, located in low redshift galaxies[29, 30, 31]. The latter type have been shown to include long (one minute) tails at flux levels well below the main short burst level[32]. The long bursts have been tied to collapsars, massive stars that rapidly collapse to black holes; the short bursts have some characteristics of merging, condensed stars.

Searches for short, optical transients have been done for some years[9, 10]. However, no objects were found until the afterglows of GRBs were first detected in 1997[33]. Now, afterglows are found routinely[34, 35]. Still, none have been found independently of the GRB gamma-ray signal. Yet, the energies of the GRBs seem to be so high that what we see as GRBs are thought to be jets of gamma-rays, boosted in apparent energy by special relativistic effects[36]. If this is the case, then there must be many more objects that we cannot detect in gamma-rays, but from which a delayed, optical afterglow might be seen as an optical transient. Evidently, no orphan afterglows, as these yet-undiscovered objects are called, have been seen.

Various attempts have been made to build modern detectors for optical flashes[15, 16, 17, 37, 38.]. The brightest afterglow from such systems found by ROTSE[39], a 9th magnitude optical counterpart to a GRB. These observing systems can also be used to search for orphan afterglows when they are not engaged in follow-ups[40]. Additionally, existing telescope systems have been engaged in the search for optical transients of GRBs. Examples include the CFHT surveys[41], the Oschin Schmidt surveys[42], the FSVS survey[43], and the Deep Lens Survey on the Blanco and Mayall 4-meter telescopes[44, 45]. The specialized, optical afterglow detectors can produce their own deep images to provide host galaxy detections, but the adapted systems (the second group in this paragraph) must either wait to image the host galaxy until the detected afterglow has faded, or use some pre-existing survey (for instance, the Digital Sky Survey[46] or the Sloan Digital Sky Survey[47, 48, 49]).

3. Science goals

3.1 Nature of the gamma-ray bursts

The independent detection of optical transients will help understand the nature of GRBs.. Here, we consider one example, orphan afterglows, those events that show an optical transient in the absence of a gamma-ray burst. Assuming the bursts are all morphologically similar, the ratio of the number of orphan afterglows to the number of GRBs is the solid angle of the beam diameter for the GRB emission divided by 4π. This beam solid angle may be as low as 0.017 radians or 1 degree[11] but could be larger. There are thought to be about 2 detectable GRB per day in the observable Universe[50], up to 30% of which may be short bursts. Here we are discussing the long bursts. The detection rate of long GRBs with SWIFT is about 0.3 per day, as it cannot simultaneously observe the entire sky. For a solid angle of 1 degree for the beams, there would then be thousands of GRBs per day (and proportionately less for larger average solid angles.) These afterglows will be faint but observable over 10^5–10^6 seconds, at levels of about 23rd magnitude[51, 52]. Evidently, a limiting magnitude of 23rd magnitude in a few tens of hours should be adequate to detect the afterglows.

There may be other events that simulate such light curves, such as cataclysmic variables[53, 54]. Confirmation of an orphan afterglow, as opposed to a stellar source, would be based on its absence in deep images that are much deeper than the transient search (showing that it is not a pre-existing, flaring star), or on the discovery of a galaxy coincident with the source, after the afterglow has faded. A survey adequate to separate point sources from high redshift galaxies would be needed, which can be provided by integrating the images of Xian over an entire season.

A telescope system with wide angle coverage and a consistent detection limit of 20th magnitude R or V (5 seconds) would be needed to detect the afterglows (by co-additions of thousands of frames for, effectively,>2 hr. integrations). If further theoretical developments suggest the glows will be fainter, then a fainter limiting magnitude will be needed.

3.2 Cosmology

Using GRBs as standard candles[55, 56], one can test the surprising results from observations of Type 1a supernovae that support cosmological models with accelerating expansion of the Universe. GRBs have so far been observed at redshifts as high as 6.4[57], whereas Type 1a supernovae probably do not occur before ~z=2. Current theory[58]suggests that the accelerating expansion does not exist beyond ~z=2. Hence, GRB observations could provide a critical test of this fundamental issue.

The combination of time resolution and continuous time coverage afforded by the instrument proposed here can also help determine the current expansion rate of the Universe (the Hubble constant at z=0[59]). Gravitationally lensed QSOs produce multiple images[60] for which the light travel times can differ by days to months. Theoretically, the onset of brightening or dimming events in the lensed QSO will therefore show up at different times in the different images owing to the fixed speed of light: the time delays depend on the Hubble constant. The effect should be independent of wavelength. Using this technique has proven to be difficult, both because of the need for continuous time coverage and the need to accurately characterize the matter distribution in the lensing object. Xian can provide the coverage and the statistics needed to address both issues.

3.3 The Blue Flash from Type II Supernovae

The light curves of the seconds-long burst that occurs when the shock of a Type II supernova breaks through the atmosphere of the star (the "blue flash") can shed light on asymmetries in the explosion, on the distribution of pre-supernova material around the star and on the formation of dust due to rapid cooling of expanding supernova ejecta at early times[61]. If these events can be detected as they rise, observations with the follow-up telescope can yield colors, polarimetric measurements and spectra in sufficient quantity to characterize the explosions and the range of variation among different events.

For Type II supernovas with red progenitors, the breakout pulse will rise in approximately 600 seconds in the observer's frame, then fall on a longer time scale. Since blue progenitors are much smaller than red progenitors, their pulses are shorter and fainter. Scaling from SNe 1993J[62] the blue flash should be detectable at <18.5 mag at z< 0.03 (the approximate distance of the Coma Cluster). An instrument scoped to detect GRB flashes at 20th mag in 5 seconds should detect a few of these events each month. The fainter, Type 1a flashes will be observable, but only a few per year are expected.

3.4 Galaxy evolution and the origin of the elements

Long-burst GRBs are bright enough in the first hours to allow the recording of high-resolution spectra[63]. At a resolving power of >3000 (100 km/sec), the interstellar lines of the GRB host galaxy can be seen. Several major surprises have come from the few spectra obtained so far and more are expected. a) The abundance of zinc (relative to hydrogen), a measure of the metalicity of an interstellar cloud, is higher in the GRB host galaxy, on average, than in QSO absorption line systems (random galaxies that lie along the QSO line of sight and are in the foreground) with comparable column densities of H I ($>10^{21}$ cm^{-2})[64]. Since zinc is probably not significantly depleted onto dust grains, this suggests that the hosts are more evolved than a random set of galaxies at these high redshifts, possibly because large numbers of core-collapse, element-producing supernovae occur together, enriching the gas.. b) Excited fine-structure excited lines of Fe II have been detected and analyzed[65] In our Galaxy, such interstellar lines are seen only in circumstellar shells, and then only rarely (e.g., in the eta Carinae region). These lines yield information on the density and radiation environment of the gas near the GRB. c) Low mass stars in the Galaxy have anomalous abundances, when [Fe/H] is less that 1/1000 of the solar iron metalicity[66]. These stars must have formed from gas clouds with those abundances, but such clouds have never been found, though we have studied thousands of random sightlines through high z galaxies[67]. GRB hosts are excellent possible sites to show such anomalous abundances. Thus, we may be able to detect the anomalous material from which the very first stars formed.

Because GRBs are so luminous, they must come from massive stars. Hence, the number of GRBs represents the high-mass end of the stellar mass function at high redshift. The nature of the high mass end of the stellar luminosity function is currently a hotly debated subject.[66]. A large sample of long burst GRBs will help define the mass of the most massive stars in the Universe.

These programs require that the spectrum of the GRB afterglow be recorded early in the event (within the first 20-30 seconds) for two reasons: a) to get the high signal-to-noise spectrum needed to see the weakest interstellar lines and thus explore the abundances of the largest number of elements possible; and b) to allow the obtaining of multiple spectra to search for time variations that will help separate the effects of gas density and ambient radiation field on the GRB ambient interstellar medium from gas in the same host galaxy, but more distant from the GRB.

Asymmetric supernova explosions produce neutrinos[68]. Since neutrino detectors are likely to be insensitive, for some time, to extragalactic supernova neutrino bursts, one may be able to demonstrate the detection sooner by examining the neutrino data streams near the time and location of GRB events and to gain a global detection of neutrinos from asymmetric supernovae. (This would require a neutrino detector on the opposite side of the Earth from the afterglow array we discuss here, or a new development that allows neutrino detection from the side of the Earth on which the array is located.)

3.5 Short bursts and gravitational waves

Merging, condensed matter stars are a potential source of gravitational waves. The short-burst objects, which probably arise in the local Universe, are candidates to produce detectable gravitational waves[69, 30]. As for the case of neutrinos, the gravitational wave detectors are still insensitive[70]. The same technique as noted for neutrino bursts, namely searching specifically the data stream of the gravitational wave detectors at the time and location of known, short GRBs may yield detection of the phenomenon, if not of specific, single sources.

3.6 Other transients

Listed in Table 1 are a number of astronomical sources that would be seen in an array adequate to see orphan afterglows. For supernova rates, we have used the Asiago catalogue of supernovae[71] to determine a lower limit to the rate of supernovae per year. From 2000 through 2005, out to 3000 km/sec or 40 Mpc, there were 79 Type II SNe, 33 Type Ib/c SNe and 43 Type Ia SNe. We scale these numbers to different volumes, consistent with the redshift limits in the table.

We note, in particular, two types of sources in which we would expect very short dips in a continuous spectrum, as opposed to bursts in an other wise blank data stream: planet eclipses and eclipses of AM CVn stars. Planet eclipses are well known. They are particularly valuable because the orbital parameters can be accurately determined, as for HD 209458b[72] and because the absorption line spectrum of the planetary atmosphere can be be detected to characterize the abundances[73.], molecular constituents[74] and the dynamical state of the atmosphere[75]. The array we discuss here will be able to detect eclipses in stars of the 12th –13th magnitude by integrating over 2-3 hour intervals of the light curves, then target those objects for radial velocity determinations and spectral studies using other telescopes. Gravitationally lensed planets will also produce obvious targets for Xian[76].

AM CVn binaries are short period binaries consisting of condensed stars that have periods as low as 10 minutes[77]. They can be found in searches for orphan afterglows[40] and, again, the eclipsing versions are of great interest. They are candidates both for emission of detectable gravity waves and for ending up as objects similar to Type I a supernovae or short gamma-ray bursts. Their spatial distribution is not known empirically, as only a handful have been detected. Given the success of SDSS[77] and ROTSE III[40] in finding these, we expect they will be abundant in this survey.

Finally, the array will detect many Type Ia and Type II/Type Ib/Type Ic supernovae. In addition to obtaining new information on their viability as standard candles, we will be able to detect the interstellar medium in nearby galaxies in which the supernovae occur[78]. There are several spectral features of the interstellar material in our Galaxy that have not been identified, let alone explained. Consider the 2175A bump in the interstellar extinction curve[79] and the diffuse interstellar bands[80]. Finding these features in other galaxies in different conditions may be key to identifying the carriers of these features. In the recent supernovae in M100 (2006 X), spectral features that are detected include the diffuse bands and the strongest interstellar CN molecular lines known[81] indicating a new extreme of conditions is being probed[82]. Such opportunities are normally rare, but should be quite common in the burst detector array. The rapid follow-up capability assures the obtaining of spectra at early times as well as late times (weeks), to look for variable interstellar lines. As in the GRB spectra noted above, detection of line variability would indicate how much of the material is near the supernova itself, and is therefore subject to intense radiation fluxes that could destroy the carriers noted above. Such clues would be invaluable in identifying the nature of the unidentified interstellar features. These features, and the 2175A bump, may hold the key to understanding the nature of the interstellar grains.

Table 1: Approximate numbers of objects per square degree per year, for selected variables.

Source	□(burst) (seconds)	Φ (square deg-yr)$^{-1}$	Limiting V magnitude
GRB (long bursts)	2-200	0.02	Gamma-rays
GRB afterglows	1000-10^5	0.01	20-23
Orphan afterglows	200-10^5	>2	23
Blue flash (red progenitor)	600	0.0005	18.1 (z=0.03)
Blue flash (blue progenitor)	60	0.0005	21.6
Type Ia SNe	10^6	2.2	23 (z=0.3)
Type II SNe	10^6	0.1	23 (z=0.1)
Gravitational Lenses, QSOs	$10^{5.6}$	10^{-2}	22
AGN	10^6	20	21
AM CVn	600s	10^{-3}:	19
Cataclysmic Variables	1800s	0.05	17.5
Planet eclipses	3600s	0.01:	13 (rocky)
Asteroids	600s	50	23

4.0 The burst detection array: Xian

4.1 The requirements

Obtaining continuous light curves for a complete sample of GRB afterglows, orphan afterglows and blue flashes, and the physical characterization of the sample requires

- wide coverage of a near cloudless, circumpolar sky;
- no daytime interruption of observations;
- a limiting magnitude in 5 seconds of 20th in V or R;
- a limiting magnitude of > 23 in 10^5 seconds;
- complete coverage of an angle of sky comparable to that achieved by gamma-ray satellites;
- the ability to follow-up detected transients with spectroscopy, photometry and polarimetry on a timescale of 10 seconds to minutes, for selected objects, and the delegation of longer timescale events to other telescopes;
- the ability to use the shortest integration to make decisions about false positives.
- overlap in time and sky coverage with a gamma ray satellite (to vet the triggering process fully and to have the information needed for the standard candle effort).

These goals can be met with an array of 400, 0.5 meter, Schmidt telescopes located on the Antarctic plateau, equipped with multi-output CCD arrays, operated in drift scan (TDI) mode.

4.2 The collaboration

Since we conclude that the system should be on the Antarctica plateau (sites comparable to Dome C or Dome A), an international collaboration is essential to the work. It is possible that the array of telescopes will be split between several sites (because of scientific requirements, logistics, communications, etc.) The best solutions will be found if everyone is in from the start, from site testing to transporting to deployment. Furthermore, the effort is more powerful if there is a gamma-ray and X-ray satellite operating and able to cover the same part of the sky while the array is operating. For a reasonable time frame, such a satellite is virtually certain to be international in scope. Additionally, the total number of transients that will be detected is too large to be followed-up with one telescope: some of the follow-up depends on long-term observations that can be done on a daily or weekly cycle from multiple, lower latitude observatories, but these too will be international in scope. It is planned that all transients will be announced in a fashion similar to what is now done with the GRB Circular Network[16].

4.3 The site

Complete light curves require complete darkness so observations are not interfered with by the daily rising of the Sun. The site must be at a location that has many months of continuous night. While the total astronomical twilight time at Dome C is actually less than experienced at mid-latitude locations, there are many months during the Dome C winter for which the short integration frames of Xian will not be sky background limited[83]. Excellent seeing is important for the follow-up telescope, as described later. While the ground-level seeing is not better than one arcsecond at Dome C[84], the majority of the turbulence is confined to within ~30 m of ground level, and the seeing above this layer is exceptional[85]. “Continuous coverage” obviously requires the least interruption by cloudy skies: the cloud cover at Dome C appears to be less than 10% [86] and is expected to be as good or better at Dome A. Land routes exist to both Dome C[87] and Dome A[88], so fuel for electricity can be carried in.

The circumpolar nature of continuous, dark, cloudless skies will produce the best light curves for characterizing the optical transients on most time scales less than two months. The Southern sky offers views of the Galactic halo, the minimum extinction window on the distant Universe, as well as coverage of the Milky Way and of the Large and Small Magellanic Clouds. Operations at such a cold site require that the number of failure points in the equipment be minimized because of the difficulty of carrying out emergency maintenance. We therefore are considering systems with no (or minimal) moving parts and passive cooling of the CCDs.

4.4 The telescopes

For the preliminary design, we have chosen Schmidt telescopes of diameter 0.5 meter and fields of view of 20 square degrees.. The aperture cannot be finally settled on without further analysis Early studies indicate that for a given solid angle of sky coverage, the cost is significantly less for the Schmidt telescopes than for other, wide-angle designs (one mirror systems with a prime focus corrector or three-mirror systems with the detector behind the primary mirror.) For robust operation, the telescopes must not move, must not have movable filter holders and must not need focusing during the winter. Figure 1 shows the ray-tracing diagram for one version of the telescope and Figure 2 shows the spot diagrams for different field radii for the optical prescription given below. The bar next to the upper left image is two arcseconds. The telescopes will have simple atmospheric dispersion correctors appropriate to the specific (unchanging) pointing of each, so all telescopes have similar point spread functions. All optics will need to be anti-reflection coated to minimize ghosts. Figure 3 is an artist’s conception of a single telescope unit (foreground) and the full array. The empty rectangle in the center is for the follow-up telescope.

Covering the full focal plane of one telescope with CCDs requires about 16,000 by 16,000 pixels, at a scale of one arcsecond per pixel, to obtain two arcsecond resolution.. The single filter could be broad band (3600-9000A). Since we may need to have two telescopes pointing at the same angle, for rejection of false positives such as cosmic rays or events in the atmosphere of Earth or the Solar System, we could get some color selection on the transients by using different filters in each of the two telescopes (red and blue filters, for example.)

The telescope design parameters are as follows:

Field of view: 5x5 degrees;
Preliminary Glass choices: corrector, N-BK7; primary mirror, Zerodur; first of two lenses to create a flat field, N-BAL4; second lens, N-BK7;
Diameter of Schmidt corrector: 0.5 meters;
Spot size: 80% of the energy in 1 pixel (so performance is seeing limited), see Figure 2.;
Wavelength range: 3860 A to 9000 A (for filterless operation);
Obscuration: 26%;
f/number.: 3.28 (for 9 micron pixels, to be reviewed when the CCD is exactly specified).

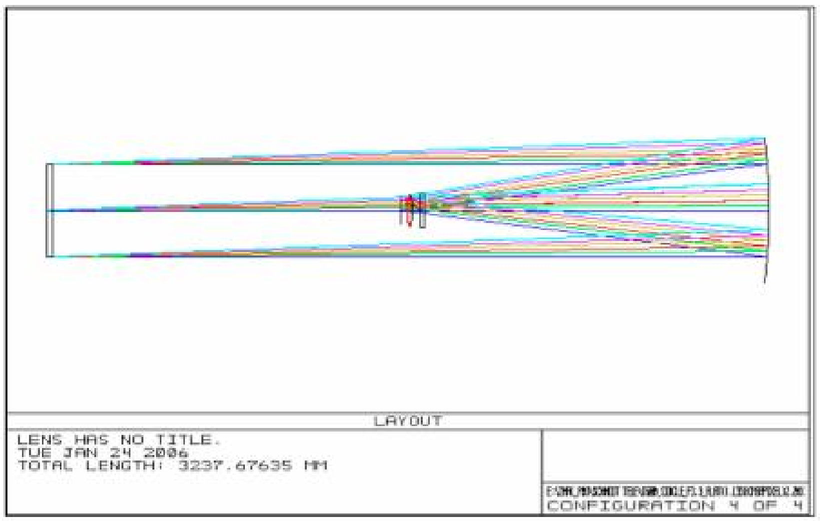

Figure 1: Ray tracing of the Schmidt design.

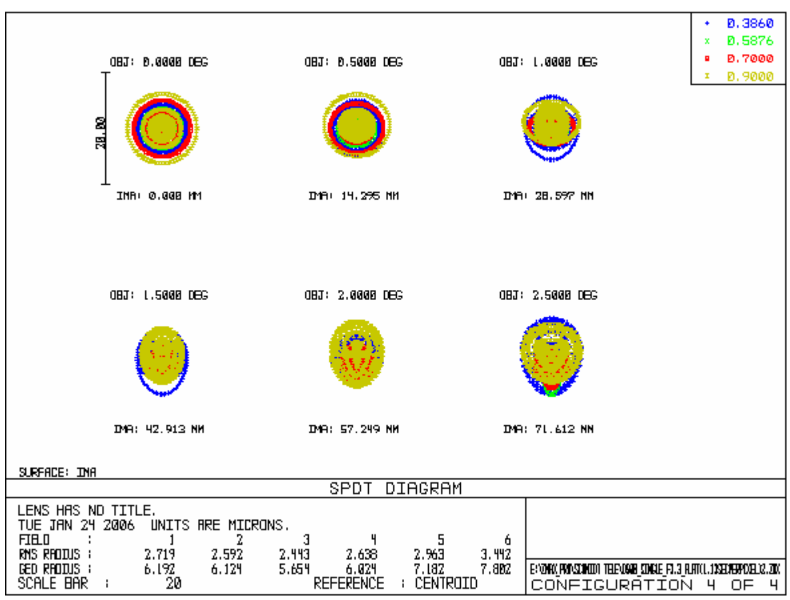

Figure 2: Spot diagrams for different field radii. Colors are for the wavelengths shown.

4.5 The detectors

We are working with Ball Aerospace and Technology Corporation to design, fabricate and package CCDs appropriate to this mission. The full ~16Kx16K array consists of 64, 4Kx1K arrays, packed as closely as possible. A layout of 32 arrays (not to scale) is shown in Figure 4. The device in the upper left includes the detail that the 1K dimension is divided into several sections, each of which has a serial register for readout and an amplifier. The fixed telescope/CCD system then moves around the sky, producing star trails with a very small arc, in 5-10 seconds. With a specification of 2 arcsec by 2 arcsec resolution, the slight smearing of the arc is negligible in the short interval. The result is 5-10 sec integrations of ~ 1 x 33 arcminute frames. These can be differenced with previous frames on the same part of the sky, to look for transients. The high time resolution data can be co-added to make frames with longer integrations and deeper limiting magnitudes, which then can be compared to trigger on events that arise on longer time-scales (orphan afterglows, type Ia supernovae, various types of variable stars, etc.), Unless storage and communication capacity is larger than is now currently available, we plan to store only light curves of detected transients and the long integration frames and to rely solely on the triggering software to extract the short term transient information.

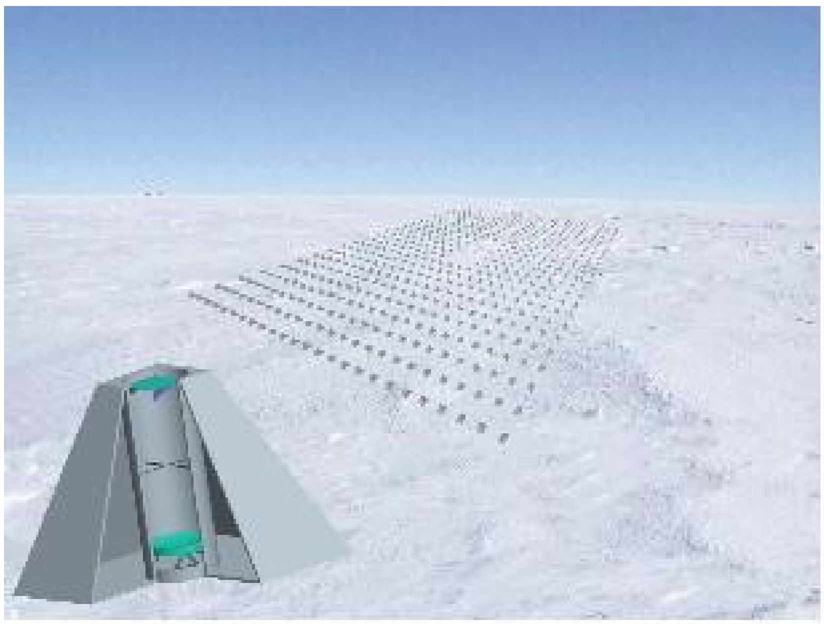

Figure 3: Artist's conception of a telescope unit (foreground) and the array on the Antarctic ice.

The power required for the electronics that drives the CCDs will be a limiting aspect of the construction of such an array in Antarctica. We expect to prototype fairly conventional electronics with the new arrays, then to move to ASICS to reduce power consumption and dissipation (the CCDs are located within the light path of the Schimdt telescopes).

The design goals for the detector array are as follows:

QE @ 9000A: >50% (it is currently thought that red sensitivity will be optimal);
Read noise: < 2 electrons, rms (with on-chip, variable gain);
Integration time: 10 seconds;
Pixel size 9-10 microns;
Well capacity: ~65 K electrons;
CTE < 0.99995;
Power dissipation per array: ~16 W;
Dark current: < 0.1 electrons per second (with Dewar);
Provision for failed amplifiers: shift charge onto the next segment (two way amplifier);
Gaps vertically: <~100 microns;

Serial registers and output amplifiers per unit within the array: :up to 13 for each 1K segment.

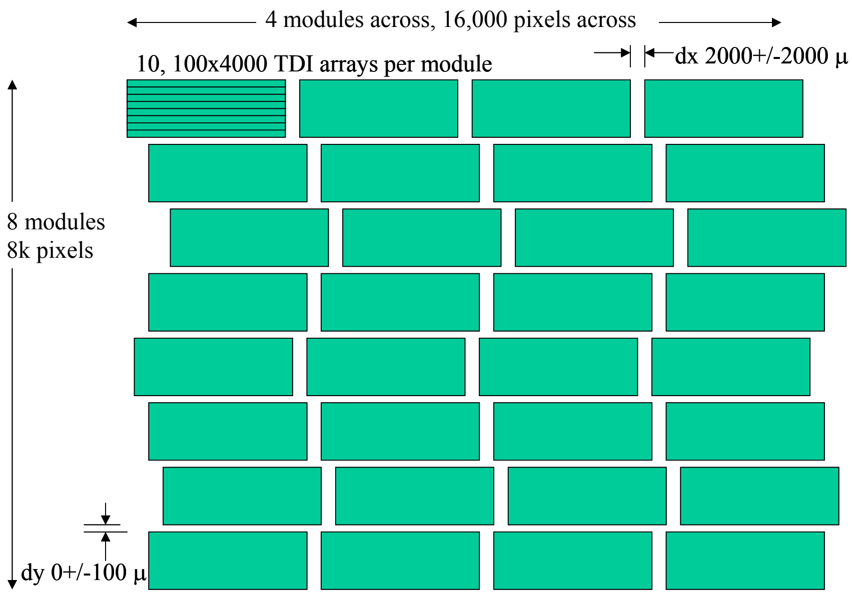

Figure 4: Layout of a 16K x 8 K CCD array (not to scale).

4.6 Triggering on bursts

In < 10 seconds, the normal corrections to CCD frames should not be necessary. Dark current will not change; sky background will not change (except for short periods of aurorae at Dome A); reflected moon light off of clouds will be defined as inoperable conditions; bias levels will not change; and plate scale will not change.. We plan to experiment, therefore, with a simple, fast trigger scheme. The alternative of doing full, photometric and astrometric reductions could, today, only be successful at some loss in triggering timescale, though that could change as computers improve. Preliminary studies of the processing of short triggers with such algorithms suggests that the processing power equivalent to a current, high-end PC will be required for each telescope/focal plane unit. While we will use programmable pipelines in the prototype array, as discussed later, we ultimately expect to use custom built processors optimized for speed and low power.

Once any event is triggered, all subsequent observations of that object will automatically be stored separately to build up the full light curve of the object in the filter(s) of Xian.

4.7 Elimination of false positives.

A major challenge is to eliminate false positives on the spot. If it takes several hours to verify a transient, the object may not be bright enough for study. Effects that could mimic transients include variable detector flaws; telescope artifacts (ghosts and diffraction spikes); processing artifacts (saturated stars, "dipoles" from variable PSFs from comparing frames); radiation hits (cosmic rays or gamma-rays from telescope parts); slow moving asteroids (in the longer, co-added integrations); glints from Earth orbiting satellites; events in the atmosphere of Earth; and, of course, true astronomical transients, such as cataclysmic variables, in the sense that they are false positives for extragalactic transients. Some of these issues have been addressed in the ROTSE III orphan afterglow searches[40]. In a search that went to magnitude 17.5, they had no, non-astronomical false positives after elimination of ~10 slow moving asteroids per day[89] using the Minor Planet web page[90]. The major source of artifacts in the SDSS supernova search[91] as been slow-moving asteroids, which have required many hours of hand processing to eliminate. The Pi in the Sky project has described the algorithms for the relatively bright false positives they detect[34] (mainly satellites). Each of these cases finds a specific limiting type of false positive that is unique to the particular search strategy and time scale they are using. The faint limit of Xian over such a large part of the sky will no doubt produce its own limiting issues, including astronomical objects that are false positives for orphan afterglows. Understanding these is the main motivation for the prototype, discussed below.

A key aspect of separating stars from extragalactic transients is the use of a deep sky image to see if any faint, quiescent source existed at the location of a transient before the event. Xian would provide an ever-deeper map for this purpose, as more and more images of the full sky area are acquired and co-added. Some regions will have to be masked so that time is not wasted on known objects: regions near bright stars may need to be blocked out, and comets might be blocked out as they occur, as might bright asteroids.

We are considering using two telescopes to cover a given part of the sky, to generically have a confirmation of any short, one-time events. We are also considering using different filters in each of the two co-pointed telescopes, to help with instant discrimination of some astronomical transients given the experience of the orphan afterglow search in the Deep Lens Survey: the three transients with the Deep Lens Survey[45] were all blue, even though they had blue and red coverage. Finally, splitting part of the array so that co-pointed telescope pairs are not co-located, but are many kilometers apart, would allow astrometric determination of the presence of asteroids as false positives. For radiation events, depending on the final type of CCD we choose, pattern recognition (in thick chips) may allow us to avoid co-pointing telescopes and, instead, to cover twice as much area of sky (8000 square degrees.)

4.8 Requirements for an on-site, follow-up telescope.

The detection of a transient in the proposed array means it is clear at the site. A co-located, dedicated follow-up telescope can be used to quickly acquire critical, physical data on the source while the source is at its brightest (in the case of the GRBs, for instance). Such a telescope should use ground layer adaptive optics or be mounted above the surface boundary layer, to allow spectrographs to have small collimators; should use selectable apertures or integral field fiber bundles to avoid acquisition overheads, and should include equipment for polarimetry, optical and IR photometry and optical and IR spectroscopy. Dichroic optics can be used to allow simultaneous, multicolor work. With modern equipment, a telescope of aperture 2.5 meters should be adequate for the envisioned follow-up. Studies of telescopes of this aperture have already been done for location at Dome C[92]. The telescope must be capable of pointing anywhere in the survey field in less than 10 seconds. If necessary, one could use multiple, identical, smaller instruments, "stationed" in small sub-areas of the survey field, to get the highest, earliest signals, with the other telescopes joining in for coincident observations over a few minutes. An automated management system will be required to choose which transients to follow on-site and which to route to other telescopes. Some objects followed up instantly will also need continued follow-up, for the longer term, using off-site telescopes. We envision follow-up of 10-12 of the highest priority sources per day, on-site

5.0 Evolution of the design

As is clear from the discussion above, a number of system design parameters need to be developed using a prototype array. We expect there to be up to three systems for this purpose: T2, two telescopes in the Southwestern USA; T5, T2 plus another 3-telescope installation, also in the Southwest; and T3, three telescopes in Antarctica. A prototype CCD array and electronics, based on the SDSS circuitry[93] would be used. T2 would have a collecting area of about 20 square degrees and would be used to develop the triggering software; to test false positive rejection schemes, including masking and the use of a deep sky map to recognize stellar transients; and to test the entire process of co-adding more and more frames and providing searches for longer term transients. The two telescopes would be able to be co-pointed, to test triggering schemes and filter strategies. Since they would have the full 0.5 meter aperture of the Xian telescopes, they would give a first look at orphan afterglows, perhaps detecting one a week, and might see a few blue flashes from the Coma cluster of galaxies, which would be provisionally targeted. T2 would be tested most thoroughly as a detector of cataclysmic variables, which simulate orphan afterglows and should be numerous. It would be used to test the level at which we can set the photometric definition of a transient, thus defining the scope of science doable with Xian. The scheme of on-site follow-up and the associated logistics would be exercised by following up transients with an on-site, pre-existing, large telescope (for instance, the flexibly scheduled 3.5 meter telescope at Apache Point Observatory). Finally, T2 and T5 will be used to define techniques and costs of Xian.

6.0 Figures of Merit

The figure of merit of a burst detector is the number of square degrees that are completely covered on some preferred time scale in one year (h [sq. degree-years])[40, 45]. The product of h (Table 2) and Φ (Table 1) is the number of sources expected in a year, where Φ is the number of sources of a given type per square degree of sky per year that can be found at the specified time scale. An efficiency factor, ε, defined as the percentage of those sources that will actually be found by a given detection system, is included in the values of h given in the Table. Table 2 lists a few observing systems already mentioned, the field of view, the spatial resolution, the search timescale, h, and the limiting magnitude at the timescale listed. Xian is the optimal combination of limiting magnitude and sky coverage among this set.

Table 2: Figures of merit for several optical transient survey systems

Observing system	Field of view	Spatial resolution (arcseconds)	Search timescale (sec)	h (sq.deg.-yr)	Limiting V magnitude
SDSS-II, SNe	1.25	1.5	$\sim10^6$	0.06	22
Deep Lens Survey	4	0.5	1300	0.16	24
ROTSE III	3.5	4	1800	1.7	17.5
T2 (APO)	20	2	30	2	20.4
T3 (Antarctica)	60	2	10	6	20
Xian	4000	2	10	1200	20
Tombo[94]	10000	4	60	4000	17
Pi in the Sky	10000	60	60	5000	12

7.0 Conclusion

Xian is a proposed array of fixed, 0.5 meter telescopes, located in Antarctica, designed to provide a complete set of light curves for supernovae of all types and for GRB afterglows. The international project will require custom CCDs and specialized software, but otherwise uses conventional parts. It should provide definitive descriptions of the nature of the GRBs, in conjunction with gamma-ray satellites, as well as of optical, orphan afterglows. It will provide extensive descriptive material on the nature of interstellar matter in the host galaxies of GRBs. Transient objects from many fields of astronomy will inevitably be detected and characterized. The success of the project depends on a robust program to follow up the detected transients, at the site as well as off-site. Many of the technical features of this project were described independently for the TOMBO project[94] (listed in Table 2) and similar solutions to a number of problems were found.

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