Astronomy with Small Telescopes

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ABSTRACT. The All Sky Automated Survey is monitoring the entire sky to about 14 mag with a cadence of about 1 day; it has discovered about 10^4 variable stars, most of them new. The instrument used for the survey had an aperture of 7 cm. A search for planetary transits has led to the discovery of about a dozen confirmed planets, so-called hot Jupiters, providing information on planetary masses and radii. Most discoveries were done with telescopes with apertures of 10 cm. We propose a search for optical transients covering the entire sky with a cadence of 10–30 minutes and a limit of 12–14 mag, with an instant verification of all candidate events. The search will be made with a large number of 10 cm instruments, and the verification will be done with 30 cm instruments. We also propose a system to be located at the L1 point of the Earth-Sun system to detect “killer asteroids.” With a limiting magnitude of about 18 mag, it could detect 10 m boulders several hours prior to their impact and provide warning against Tunguska-like events, as well as provide news about spectacular but more modest, harmless impacts.

1. INTRODUCTION

The goal of this paper is to point out that there are many tasks for which small and even very small telescopes are not only useful, but even indispensable. Following are several examples.

The Gaustad et al. (2001) work on Hα emission was fundamental in accounting for the Galactic foreground. Therefore, it was essential for cosmology (Finkbeiner 2003); it was done with a 52 mm lens. The same instrument was used to map the planetary nebula Abell 36, which was found to be far more extended than thought previously (McCullough et al. 2001). Optical flashes from cosmological distances were detected by Akerlof et al. (1999; Robotic Optical Transient Search Experiment [ROTSE]) and Jelínek et al. (2006); the searches reached 8.9 and 10.1 mag, respectively, and used 100 mm optics. The flashes were due to gamma-ray bursts 990123 and 060117, respectively. The recent optical flash at about 5 mag had an unknown origin (Shamir & Nemiroff 2006). It was registered with two all-sky cameras with 8 mm fish-eye lenses: one at Cerro Pachon, Chile, and another at La Palma, Spain. The flare was not detected at Cerro Paranal, but the exposures were not coincidental, so there is no inconsistency.

Schaefer (1989) and Schaefer et al. (2000) compiled a list of very compelling cases where historical evidence implied unusual brightening of otherwise ordinary bright stars. Unfortunately, none of these cases were rapidly followed up spectroscopically or photometrically. There was no rapid follow-up in the recent case of Shamir & Nemiroff (2006). It is clear that without instant follow-up all those events remain at the level of gossip.

However, for a number of years optical afterglows were successfully followed up by many groups. The difference was due to gamma-ray bursts acting as a trigger, making it possible to concentrate on a relatively small area of sky. If the entire sky were well covered down to some magnitude, and the variability of all stars were known, the recognition of transients would be much easier. It is one of the goals of this study to make the whole sky familiar at gradually fainter magnitudes. This task is familiar: similar goals are advocated by LSST (Large Synoptic Survey Telescope; Claver et al. 2004), PanSTARRS (Panoramic Survey Telescope & Rapid Response System; Kaiser 2004), and the SkyMapper Telescope (Schmidt et al. 2005). The major difference is the cadence: the three megaprojects propose imaging the entire sky in a week. We suggest imaging the sky once every minute or once every 15 minutes, depending on how deep we would go. Of course, all the proposed megaprojects will reach vastly fainter magnitudes, and typically they will saturate below 15 mag. The huge differences in cadence and magnitude make these projects complementary rather than competitive.

In the following sections we present several examples of a successful implementation of small instruments. The ASAS (All Sky Automated Survey) and NSVS (Northern Sky Variability Survey), with ranges of about 14 mag and cadences of about 1 day, provide examples of relatively low accuracy surveys. A search for planetary transits that concentrates on a very small part of the sky achieves very high precision photometry. The above surveys are covered in §§ 2 and 3. In addition, we propose two future projects: the search for all untriggered optical flashes and a new approach of dealing with “killer aster-
oids”; these are covered in §§ 4 and 5. Finally, § 6 concludes the paper with a discussion.

2. ASAS AND NSVS

The ASAS is an example of a modest system that already exists, and it was created to fill a gap in the sky variability. It has already produced results: catalogs of bright variable stars (Pojmański 1997, 1998, 2000, 2002, 2003; Pojmański & Maciejewski 2004, 2005; Pojmański et al. 2005).

ASAS is a long-term project dedicated to the detection and monitoring of the variability of bright stars. It uses telescopes with apertures of 7 cm, focal lengths of 20 cm, and 2K x 2K CCD cameras with 15 μm pixels from Apogee. The standard V-band and I-band filters are used. The I-band data are still being processed, but all V-band data have already been converted to catalogs of variable stars. ASAS reaches 14 mag stars in 2 minute exposures over a field of view of 9 deg2. More information about ASAS is provided on the World Wide Web.1 ASAS has already been used to address some problems in the domain of contact binaries (Paczyński et al. 2006).

In addition to discovering over 50,000 variable stars in the V band, ASAS also has a limited ability to react to new phenomena: it has discovered two comets and a number of novae and dwarf novae stars. However, the software has not been developed yet for a fully automatic recognition of new phenomena. Its main virtues are a low cost and reliability; G. Pojmański is required to visit the Las Campanas Observatory just once every 2 years. The OGLE (The Optical Gravitational Lensing Experiment)2 observer who happens to be on duty opens the dome for the OGLE telescope, and this automatically opens ASAS. About once every week the OGLE observer changes the data tape or reboots the ASAS computer.

G. Pojmański has recently (2006 June 1) developed ASAS-N at the Faulkner North site at Haleakala on Maui (Hawaii), courtesy of W. Rosing, to cover the entire sky with observations. The optics have been upgraded to an aperture of 10 cm, with the same focal length. Just like the ASAS at Las Campanas, the system uses two cameras, one for the V band and another for the I band.

The idea is to have ASAS as a system to operate indefinitely, as stars vary on all timescales. The practical issue is to keep the operating costs very low, so the project can continue forever, with modest upgrades from time to time. Hopefully, other astronomers, perhaps even amateurs, will join ASAS-like projects, expanding it to all time zones and providing around-the-clock time coverage.

The NSVS (Wozniak et al. 2004) provided a database of photometric measurements covering a time interval of 10 months of ROTSE-I data and a magnitude range from 8 to 15.5. While the original data were obtained with no filter, the 2MASS (Two Micron All Sky Survey) data can be used to obtain color information. Combined with the current ASAS data, the NSVS provides a 10 month coverage of the variability of the entire sky. However, within a year ASAS will expand its coverage of the northern sky and will provide two-band photometry for the full sky. Still, the NSVS will remain forever as an archive: there is no way to go back in time.

The usefulness of this activity can be quantified: so far ASAS has been used in various papers and notes listed on the Smithsonian/NASA Astrophysics Data System (at least 134 times) and the NSVS (at least 52 times).

ASAS and NSVS make the sky well studied for variabilities down to about 14 mag with a cadence of about 1 day. This may be a good starting point to search for many more rapid transients, with better time coverage and from many locations. There is no obvious limit to this activity.

3. A SEARCH FOR PLANETARY TRANSITS

The search for planets transiting solar-type stars produced spectacular results. The importance of transits is due to the fact that these are the only planets for which accurate radii and masses can be obtained. The first discovery was found using radial velocities to select the candidate HD 209458b (Mazeh et al. 2000; Charbonneau et al. 2000; Henry et al. 2000). This was a bright star, suitable for detailed photometry and spectroscopy. Two more cases of a transit selected through radial velocity studies have been found: HD 189733b (Bouchy et al. 2005) and HD 149026b (Sato et al. 2005). These stars are very bright too.

So far 11 cases of planetary transits have been discovered, first photometrically and confirmed spectroscopically later. Most of them were detected with 10 cm telescopes: TrES-1 (Alonso et al. 2004), XO-1b (McCullough et al. 2006), TrES-2 (O’Donovan et al. 2006), HAT-P-1b (Bakos et al. 2006), and WASP-1b and WASP-2b (Collier et al. 2006). I expect that the number of such discoveries will increase, now that astronomers have learned how to make accurate photometry with wide-angle telescopes. The advantage of 10 cm telescopes is that they cover a large area in the sky, close to 100 deg2, and make the search broad. Still, it will take many years to search the sky for planetary transients.

These are also the five objects first selected as candidates for planets by OGLE: OGLE-TR-10b (Udalski et al. 2002c; Bouchy et al. 2005; Konacki et al. 2005), OGLE-TR-56b (Udalski et al. 2002b; Konacki et al. 2003), OGLE-TR-11b (Udalski et al. 2002a; Pont et al. 2004), OGLE-TR-113b (Udalski et al. 2002a; Bouchy et al. 2004; Konacki et al. 2004), and OGLE-TR-132b (Udalski et al. 2003; Bouchy et al. 2004). All these are relatively faint, as the stars were monitored with a relatively large 1.3 m telescope. Yet, for a year or two OGLE was dominating the field of planetary transients, providing masses and radii for planets.

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1 See http://www.astrouw.edu.pl/~gp/asas/asas.html or http://archive.princeton.edu/~asas.
2 See http://www.astrouw.edu.pl/~ogle or http://bulge.astro.princeton.edu/~ogle.
Very recently, Sahu et al. (2006) used the HST (Hubble Space Telescope) to search for transiting planets at 19–26 mag: a survey known as the Sagittarius Window Eclipsing Extrasolar Planet Search (SWEEPS). Despite finding a few transiting candidates, spectroscopic follow-up and confirmation of the SWEEPS candidates is currently out of reach, since the HST represents the extremely high end in both spatial and photometric sensitivity. Therefore, the SWEEPS planetary candidates must remain candidates for some time to come.3

It is clear that the best way to search for planetary transits is to conduct it with many small telescopes, with apertures of 10 cm or so, and large CCD cameras. The many recent discoveries are the best case I know of showing that the scientific advantage of small instruments is beyond any doubt. Of course, there is a need to do spectroscopic follow-up with bigger telescopes.

### 4. A SEARCH FOR OPTICAL FLASHES

The best known optical flashes are the gamma-ray burst (GRB) afterglows. A compilation of the results from the GCN (GRB Coordinates Network) archive by R. Quimby & E. McMahon is available on the World Wide Web.4 It indicates that a large fraction of optical afterglows decay as $F \sim 1/t$ initially, and as $F \sim 1/t^2$ after the break. Most afterglows are detectable only with large apertures, although there have been several very bright optical transients (OTs): OT 990123 (Akerlof et al. 1999; 9 mag), OT 060117 (Jelíněk et al. 2006; 10 mag), and OT 061007 (Mundell et al. 2006, $R = 10.3$ mag; Schady et al. 2006, $V < 11.1$ mag).

At this time, the search for afterglows is frustrating, as most of the time no afterglow is detectable, and most of the time the instruments are idle. I think another mode of search might be more satisfactory: to image the entire sky for whatever transients come around. There is no fundamental rule that would restrict astronomy to just one type of flash. As far as I know, this idea was seriously implemented only by R. Nemiroff and his associates, with the concept of CONCAM (CONtinuous CAMera; the Isaac Newton Group’s all-sky camera), a camera with a fish-eye lens monitoring the entire sky in about a dozen observatories (Nemiroff & Rafert 1999). Following several frustrating years there was finally a success: a paper announcing the discovery of an optical flash of about 5 mag (Shamir & Nemiroff 2006). In their abstract, the authors did not suggest an astronomical discovery, even though they recorded an almost identical flash from Chile and from the Canary Islands.

However, there was an obvious problem with CONCAM: there was no automatic follow-up that would provide proof that the flash was real. The problem with CONCAM, as well as all those stars of Schaefer (1989) and Schaefer et al. (2000), was that there was no instant follow-up. It would be great to have spectroscopic verification, but a photometric verification should be just as good, provided a larger instrument is available to follow a promising candidate event down to 18 mag, or even down to 15 mag. The obvious problem is to sort out which flashes are real and which are artifacts. I am convinced that this problem can be handled. After all, these problems will have to be addressed with LSST, PanSTARRS, and the SkyMapper, except that they will be much tougher to handle with big instruments; there will be more candidate flashes that are sampled very rarely, with a cadence of a week or so. The sky variability in a short time domain is hardly explored. It makes sense to explore the sky gradually, initially at the bright end, and gradually to go deep.

The optical GRB afterglows are not the only optical sources that may be discovered, as demonstrated by Shamir & Nemiroff (2006) with their 5 mag flash. Systems similar to CONCAM should be used to monitor the sky at all timescales. We do not know the range of various optical flashes, GRB afterglows, and other phenomena. First, we should familiarize our system with the sky at a given magnitude that we can conveniently reach. As a by-product we shall learn not only about the stars, including all variables, but also asteroids, comets, etc.: all kinds of “normal” transients.

Every instrument has a range of applicability: magnitude range, the cadence, sky coverage, etc. We have little information about the best range of parameters in which to search, so we should search as broadly as we can afford, in as many different parameters as we possibly can. The new Apogee CCD cameras with 4K × 4K pixels of 9 μm on a side cost about $15,000. Combining these cameras with telephoto lenses of different focal lengths, we can reach different magnitudes. For example, using a lens with $f = 200$ mm, we can reach down to 15 mag in a few-minute exposure. With faster optics and smaller apertures, we can reach brighter stars faster. For example, we can image all stars brighter than 10 mag every minute or so, providing a “continuous record of the sky” (Nemiroff & Rafert 1999). This would make it possible to search the sky for optical flashes with verification. Gradually, improved optics will allow, among other things, a search for optical afterglows without GRB triggers.

### 5. KILLER ASTEROIDS

The search for so-called killer asteroids, with diameters in excess of 300 m and Earth-crossing orbits, is one of the most active areas of solar system research, with over 3500 objects discovered as of 2005 December.5 The rate of collisions of 1 km asteroids with the Earth is uncertain. It is estimated to be once every $10^5$ yr by Rabinowitz et al. (2000), once every half a million years by Ivezić et al. (2001), and once every 3 million years by Brown et al. (2002). Currently, there are

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3 Of course, these are very useful data about various types of variable stars, and in particular hundreds of short-period binary stars.

4 See http://grad40.as.utexas.edu/~quimby/hu2006.

5 See http://neo.jpl.nasa.gov/neo/number.html.
approximately 10 NEO (near-Earth object) search programs. These discoveries provide information about possible or probable impacts in the distant future, but none of them have predicted any actual impact so far.

Collisions with $D = 1$ km asteroids are likely to be globally catastrophic, but they are very rare according to all estimates. Much more common are Tunguska-class events (Chyba et al., 1993), which occur every 1000 yr according to Brown et al. (2002), and more frequently according to Rabinowitz et al. (2000) and Ivezić et al. (2001). While these are of no global concern, they would be locally catastrophic, equivalent to an explosion of a major thermonuclear weapon, $\sim 10$ megatons of TNT, i.e., 500 times more powerful than the Hiroshima bomb. Even far less energetic events could be locally catastrophic. More information about meteor phenomena can found in Cplecha et al. (1998).

As far as I know there is no ongoing search for such small, $\sim 10$–$50$ m size objects, which could provide advance warnings of their approach and impact. While even a Tunguska-class asteroid is not very likely to strike within a decade, it would be a major embarrassment for the astronomical community not to provide a timely prediction of a strike.

This is an outline of a project to detect cosmic rocks several hours, perhaps several days, prior to the impact, and to provide an advanced warning to the local population (e.g., Paczyński 1997, 2000, 2001). Smaller objects might also be detected, and the prediction of the time and location of harmless but spectacular fireballs could provide astronomical entertainment to the general public (e.g., Foschini 1998; Tagliaferri 1998).

Brown et al. (2002) estimated the flux of small NEOs colliding with the Earth based on the record of events detected by the US Department of Defense and Department of Energy. The events were recorded with space-based systems with infrared detectors in geostationary orbits (Defense Support Program). The energetics of infrared flashes were converted to the kinetic energy of the bolides and into their likely size. In total, $\sim 300$ spectacles were recorded from 1994 February to 2002 September, but none were predicted.

While Brown et al. (2002) and Ivezić et al. (2001) give discordant estimates for the collision rate with $D \approx 1$ km asteroids, their estimates for small, $d \approx 10$ m rocks are similar. The cumulative rate can be approximated as

$$N \approx 0.1 \left( \frac{D}{10 \text{ m}} \right)^{-2.5} \text{yr}^{-1},$$

i.e., rocks 10 m in size strike the Earth every 10 yr, on average. It takes $\sim 24$ hr to move a distance of four LDs (lunar distances) at the velocity of 20 km s$^{-1}$. This gives us little time to provide a warning.

The apparent magnitude of an object with diameter $D$ located in the antisolar direction at a distance $d$ is estimated to be

$$V \approx 18 - 5 \log \left( \frac{D}{1 \text{ km} \ AU} \right) \approx 15 - 5 \log \left( \frac{D}{10 \text{ m} \ LD} \right)$$

$$\approx 18 - 5 \log \left( \frac{D}{10 \text{ m}} \right) \left( \frac{0.01 \text{ AU}}{d} \right),$$

where AU is the astronomical unit, which is approximately equal to the inner Lagrangian point in the Earth-Sun system. It is also the location of the space probe SOHO (Solar and Heliospheric Observatory; Fleck 2004). The apparent magnitude can be estimated by noting that the full Moon is $\sim 12.3$ mag, and a rock with a 10 m diameter at the Moon distance will be 15 mag, assuming the Moon’s albedo.

The best view for detection of a space rock is at the full Moon. At a quarter Moon the brightness is 10 times smaller, and at new Moon the rock is not visible at all. Yet, Earth is under bombardment all the time, from the solar as well as the antisolar direction. There is only one way to provide permanent protection: go to space, preferably to the L1 point, from which all space rocks are well illuminated, and monitor approximately $\pi$ sr. Adopting the L1 point to look for the boulders aimed at Earth, we can detect a rock with a 10 m diameter as a star of 18 mag, with a modest change depending on its phase angle. A rock 100 m across would be seen as a 13 mag star from the inner Lagrangian point.

Obviously, there are problems. The number of speeding rocks will be huge, but most of them will miss the Earth by a large margin. Some can be rejected right away, but many will have to be followed to make sure they miss the Earth. As the positions of all objects will vary all the time, it will be necessary to image them many times a day in order to be able to keep track of them. The estimate of images required is well beyond the task of this paper.

A very obvious question is: Will it be better to use a relatively large telescope, say 50 cm in diameter, to monitor 18 mag objects, or will it be better to have a number of smaller instruments to do the task? In any case, the sky will have to be imaged many times every day. Assuming that monitoring will cover $\pi$ sr of the sky centered on Earth as seen from the L1 point, this will be a serious number-crunching project, and an even more serious programming task. However, if we are serious about killer asteroids, this is the best way to handle the danger. Note that this is the most likely danger that has origins in space, not stellar explosions or gamma-ray bursts.

**6. DISCUSSION**

The first three sections—the introduction, the description of ASAS and NSVS, and the description of planetary transit—cover the practical applications of small telescopes, which generate interesting results. These applications will continue, and
the use of these small instruments in the future is without any doubt.

The subsequent two sections discuss the expectations. The search for optical transients is likely to be developed by W. Rosing et al. (2006, in preparation) using small instruments. The future results by LSST, PanSTARRS, and the SkyMapper will be complementary, with their magnitude range and a cadence of approximately 1 week.

The proposed approach to killer asteroids will require much study in order to evaluate the practical aspects of the proposed scheme. I am optimistic. The search for oncoming boulders may provide considerable excitement, in particular for those that result in very bright optical flashes, such as those of Foschini (1998) and Tagliaferri (1998), except that these flashes will be predicted in advance.

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