THE FUTURE OF MASSIVE VARIABILITY SEARCHES

BOHDAN PACZYŃSKI

Princeton University Observatory, Princeton, NJ 08544–1001, USA;
E-mail: bp@astro.princeton.edu

Abstract

This is a personal review of various issues related to massive photometric and astrometric searches. A complete inventory of variable stars down to almost any magnitude limit will improve our understanding of the stellar evolution and the galactic structure. A search for detached eclipsing binaries will improve the distance scale, the value of the Hubble constant, and the age of the oldest stars. A search for supernovae will help the determination of cosmological parameters Ω and Λ. A search for microlensing events will provide insight into the stellar mass function, dark matter, and may lead to a discovery of earth-mass planets.

1 Introduction

Many of the most interesting new results in astrophysics were obtained with survey projects, opening up a new range of photon energies, lower flux limits, more precise position measurements, etc. A rapid increase of the power of computers, and a rapid decrease of their cost, opened up yet another dimension for the surveys: the number of objects that can be measured and monitored. The massive searches for gravitational microlensing have lead to the detection of over 100 microlensing events by the MACHO, OGLE, DUO, and EROS collaborations (Paczyński 1996b and references therein). These projects demonstrated that automated real time processing of photometric measurements of up to \( \sim 10^7 \) stars every night is possible with very modest hardware and operating costs. They also demonstrated that while the original goal of finding the very rare microlensing events has been reached, much more has been accomplished; a very large diversity of scientific results was obtained, related to the galactic structure and stellar variability. New programs have been stimulated, providing new ways to improve the cosmic distance scale, the age estimates of the oldest stellar systems, a robust determination of the stellar luminosity function and mass function.

The microlensing searches concentrate on small selected areas, the galactic bulge and the Magellanic Clouds, and they reach down to \( \sim 20 - 21 \) mag stars. Note that the total number of all stars over the whole sky which are brighter than 15 mag is \( \sim 2 \times 10^7 \) (Allen 1973), of which only \( \sim 50\% \) are visible from any given site on any given night. Therefore, the processing power comparable to that of the existing microlensing searches can allow nightly photometric measurements of all stars brighter than \( \sim 15 \) mag. An incremental increase in the data acquisition and data processing rates can gradually bring into the monitoring programs all objects brighter than magnitude 16, 17, etc. At every step there are new and interesting scientific issues to address.

Some recent and planned large scale optical surveys and searches are described in the next section. Some examples of possible scientific programs feasible at various magnitude limits are described in section 3, and some possible technical implementations are described in section 4.

\(^{1}\text{Invited talk, presented at the 12th IAP Colloquium: Variable Stars and the Astrophysical Returns of Microlensing Surveys.} \)
2 The Past and Current Massive Monitoring Programs

Most variable stars which can be found in the catalogues were discovered with massive photographic monitoring programs, carried out over many decades at Harvard College Observatory, Sonnenberg Observatory, and many other observatories. The majority of supernovae were discovered with photographic plates or films, even though many were also discovered visually or with CCD detectors.

Recently, a number of massive photometric searches for gravitational microlensing events were begun with either photographic or CCD detectors: DUO (Alard 1996b), EROS (Aubourg et al. 1993), MACHO (Alcock et al. 1993), and OGLE (Udalski et al. 1992). These projects not only revealed a number of microlensing events (Alcock et al. 1993, 1995a,c, Pratt et al. 1996, Aubourg et al. 1993, Alard 1996b, Udalski et al. 1993, 1994a), but also a huge number of variable stars (Udalski et al. 1994b, 1995a, Alard 1996a, Alcock et al. 1995b, Grison et al. 1995, Cook et al. 1996, Kalužny et al. 1995a). The total number of variable stars in the data bases of these four collaborations can be estimated to be about $10^5$, most of them new.

A very important aspect of these projects is their very large scale, so the search for variable objects has to be done, and is done, with computer software, following some well defined algorithms. This means that the sensitivity of the searches to detecting variables of any specific kind can be well calibrated. So far a preliminary calibration was done only for the sensitivity to detect microlensing events (Udalski et al. 1994a, Alcock et al. 1995b). A similar procedure can be done, and certainly will be done, to determine the sensitivity to detect variable stars of various types, magnitudes, amplitudes, periods, etc. This is a new possibility, rarely if ever available to the past photographic searches.

In addition to massive searches there are a number of on-going observing programs of selected groups of known variables, in order to understand their long term behavior. Many such observations are done with robotic telescopes, looking for supernovae, optical flashes related to gamma-ray bursts, near earth asteroids, and many other variable objects (Hayes & Genet 1989, Honeycutt & Turner 1990, Baliunas & Richard 1991, Filippenko 1992, Perlmutter et al. 1992, Schaefer et al. 1994, Akerlof et al. 1994, Hudec & Soldan 1994, Kimm et al. 1994, Henry & Eaton 1995). Many robotic telescopes are operated by amateur astronomers. The CCD cameras and computers became so inexpensive that they can be afforded by non-professional astronomers, or by groups of non-professional astronomers.

One of the most important massive observational programs is being done with the satellite Hipparcos, which will provide excellent astrometry and photometry for the brightest $10^5$ stars over the whole sky, and less accurate data for another one million stars, as described in many articles published in the whole issue of Astronomy and Astrophysics, volume 258, pages 1 – 222.

There are many new massive searches being planned by many different groups. These include people who are interested in detecting possible optical flashes from cosmic gamma-ray bursts (Boer 1994, Otani et al. 1996), people who search for supernovae, general variable stars, near-earth asteroids, distant asteroids, Kuiper belt comets, etc. Perhaps the largest scale survey project is the Sloan Digital Sky Survey (Gunn & Knapp 1993, Kent 1994). The All Sky Patrol Astrophysics (ASPA, Braeuer & Vogt, 1995) is the project to replace the old photographic sky monitoring with the modern CCD technology. It is not possible to list all the proposed programs, as there are so many of them. They have a large variety of scientific goals, but they all have one thing in common: they are all aimed at the automatic photometry and/or astrometry of a huge number of objects on a sustained basis, and most of them are proposing a search for some rare, or extremely rare type of objects or events.

3 Scientific Goals

There are different types of scientific results which will come out of any major survey, including the future all sky monitoring programs.

First, if a survey is done in a systematic way which can be calibrated, then it will generate large complete samples of many types of objects: ordinary stars of different types, eclipsing binaries, pulsating stars, exploding stars, stars with large proper motions, quasars, asteroids, comets, and other
types of objects. Such complete samples are essential for statistical studies of the galactic structure, the stellar evolution, the history of our planetary system, etc.

**Second**, the identification of more examples of various types of objects will make it possible to study them in great detail with the follow-up dedicated instruments and will help to improve the empirical calibration of various relations. Bright detached eclipsing binaries and bright supernovae are just two examples of objects which call for the best possible calibration.

**Third**, some very rare objects or events will be detected. Some may uniquely assist us in understanding critical stages of stellar evolution. A spectacular example from the past is FG Sagittae, a nucleus of a planetary nebula undergoing a helium shell flash in front of our telescopes (Woodward et al. 1993, and references therein). Some may provide spectacles which bring astronomy to many people. A few recent examples are the supernova 1987A in the Large Magellanic Cloud, a collision of the comet Shoemaker-Levy with Jupiter in the summer of 1994, and the bright comet Hyakutake in the spring of 1996.

**Fourth**, fully automated real time data processing will provide instant alert about variety of unique targets of opportunity: supernovae, gravitational microlensing events, small asteroids that collide with earth every year, etc. Such alerts will provide indispensable information for the largest and most expensive space and ground based telescopes, which have tremendous light collecting power and/or resolution but have very small fields of view.

**Fifth**, the archive of photometric measurements will provide a documentation of the history for millions of objects, some of which may turn out to be very interesting some time in the future. The Harvard patrol plates and the Palomar Sky Survey atlas provide an excellent example of how valuable an astronomical archive can be.

**Sixth**, some unexpected new objects and phenomena may be discovered. There is no way to know for sure, but it is almost always the case that when the amount of information increases by an order of magnitude something new is discovered.

One may envision beginning the all sky variability survey with very low cost equipment: a telephoto lens attached to a CCD camera, with the cost at the level of a personal computer. A "low end" system can easily record stars as faint as 14 magnitude. Naturally, many small units are needed to monitor the whole sky.

It is useful to realize how many stars there are in the sky as a function of stellar magnitude. This relation is shown with a solid line in Figure 1, following Allen (1973). There are 10\(^3\), 10\(^4\), 10\(^5\), 10\(^6\), 10\(^7\), 10\(^8\) stars in the sky brighter than approximately 4.8, 7.1, 9.2, 11.8, 14.3, and 17.3 mag, respectively. Also shown in the same Figure are the numbers of know binaries of three types: Algols, contact binaries (W UMa), and binaries with spotted companions (RS CVn). Note that among the brightest stars the fraction of these binaries is very high, presumably because these stars, with \(m < 6\) mag, are studied so thoroughly. When we go faint the incompleteness sets in.

In the following sub-sections I shall discuss a few specific types of variables, pointing out to various indicators of the incompleteness. All numbers are taken from the electronic edition of the 4th General Catalogue of Variable Stars as available on a CD ROM (Kholopov et al. 1988).

3.1 RS Canum Venaticorum Binaries

The incompleteness is most dramatically apparent for the RS CVn type binaries, where very few stars fainter than 5th magnitude are known. These variables have small amplitudes, typically only 0.1 or 0.2 mag, so they cannot be found with photographic searches. A systematic CCD search should reveal lots of such variables in the magnitude range 6 – 10, and of course even more among fainter stars. Periods are typically a few days to a few weeks.

The nearly sinusoidal light variations are believed to be caused by rotation, with the stellar surface covered with large, irregular spots, similar to those found on the sun, but much larger. The spot activity varies with time, possibly in a way similar to the solar cycle. These red subgiant stars have hot winds, with strong X-ray emission. It is thought that this activity is due to relatively rapid rotation combined with convective envelopes. There are related stars of the FK Comae type which are
Figure 1: The number of all stars in the whole sky in one magnitude bins is shown with a solid line. The number of Algol type binaries listed in the General Catalog of Variable Stars is shown with open circles. The number of contact binaries (W UMa stars) and of RS CVn (spotted) binaries is shown with filled circles and with star symbols, respectively. Note that for $m > 9 \text{ mag}$ the fraction of all stars which are either Algol or contact type binaries decreases rapidly, presumably because of incompleteness of the variable star catalog. The incompleteness of RS CVn type binaries becomes obvious already for $m > 6 \text{ mag}$.

Figure 2: The distribution of known contact binaries (W UMa stars) which are fainter than 12 mag is shown in galactic coordinates. The celestial equator is marked with a dashed line. The patchy distribution of known systems is a clear indication of catalog’s incompleteness.
single, but rapidly rotating. These were presumably produced by mergers of two components of close binaries. Photometrically it is difficult to distinguish these two types of variables, unless the presence of eclipses reveals the binary nature, and therefore the RS CVn classification.

Long term monitoring of RS CVn and FK Com type variables would provide information about stellar magnetic cycles, and so it would help us understand the nature of the solar cycle.

3.2 Contact Binaries

Contact binaries, known as W Ursae Majoris stars are very common. Recent studies indicate that one out of 140 solar type stars is a member of a contact binary (Rucinski 1994). The Fourth edition of the General Catalog of Variable Stars (Kholopov et al. 1988) lists a total of over 28,000 variables, only 561 of them classified as EW type (i.e. W UMa type); 530 of these have binary periods in the range 0.2 - 1.0 days. The number of these stars is shown as a function of their magnitude in Figure 1. Also shown is the estimate of the total number of all stars in the sky according to Allen (1973). At the bright end, for $m < 9$ mag, there is one known contact binary per $10^3$ stars. Below magnitude 9 the fraction of known contact binaries declines rapidly. Therefore even at $\sim 10$ mag we may expect many new W UMa systems to be discovered.

The incompleteness of current catalogs becomes striking at $\sim 12$ mag, as clearly shown in Figure 2, presenting the distribution of those bright contact binaries in the sky in the galactic coordinate system. The clustering is caused by the non-uniform sky coverage by the past searches.

Contact binaries are very easy to find. Their brightness changes continuously with a typical amplitude of $\sim 0.6$ mag. A few dozen photometric measurements are enough to establish the period and the type of variability. The fraction of stars which are contact binaries is likely to be reasonably constant well below the 9th magnitude. A simple inference from Figure 1 is that there are likely to be $\sim 10^3$ new contact binaries to be discovered which are brighter than 14 mag. If the search is done with a well defined procedure which can be calibrated then these $\sim 10^3$ systems would be very valuable for a variety of studies.

The origin, structure and evolution of contact binaries is poorly understood. It will be very important to find out if there are non-contact binaries which might be precursors of contact systems, as expected theoretically. In some theories the thermal evolution of contact systems should periodically take them out of contact, dramatically changing the shape of their light curves, but it is not known if these theories are correct. Only observational evidence can solve this and many other puzzles of W UMa binaries.

It is very likely that contact systems, once properly understood, will turn out to be good "standard candles", and as such they could be used as tracers for studies of the galactic structure. There is already evidence for a fairly good period - color - luminosity relation (Rucinski 1994).

3.3 Algols

Variable stars of the Algol type are eclipsing binaries. They are most often of the semi-detached type, i.e. one component fills its Roche lobe and the gas flows from its surface towards the second component under the influence of tidal forces. The incompleteness of the current catalogs can be appreciated in many ways. First, the fraction of stars which are known to be Algols declines as a function of apparent magnitude, as clearly seen in Figure 1. Second, the apparent distribution of moderately bright Algols, in the magnitude range 12-13, is clearly clustered in the sky. Finally, the distribution of Algols in the eclipse depth - binary period diagram shows a dramatic difference between the bright ($m < 5$ mag), and moderately bright stars ($9.5 < m < 10.0$ mag), with the long period systems missing from the fainter group - this is most likely caused by the difficulty of detecting eclipses which are spaced more than a few months apart. Also, eclipses shallower than 0.25 mag dominate the bright sample but are entirely missing from the fainter sample, because photographic searches could not reliably detect low amplitude variations.
3.4 Detached Eclipsing Binaries

In contrast to contact binaries and most Algols the detached eclipsing binaries are much more difficult to find as their eclipses are very narrow, and their brightness remains constant between the eclipses. In detached systems both stars are much smaller than their separation. Typically ~ 300 photometric measurements have to be made to establish the binary period, and roughly one out of 10^3 stars is a detached eclipsing system (Kalužny et al. 1995b, 1996a,b). The fraction of such binaries which are missing in the catalogs is likely to be even larger than it is for contact systems.

Detached eclipsing binaries are the primary source of information of stellar masses, radii and luminosities (Anderson 1991, and references therein). When properly calibrated they are to become the primary distance and age indicators (Guinan 1996, Paczyński 1996a,d, and references therein). The first such systems were recently discovered in the Large Magellanic Cloud (Grison et al. 1995) and in a few globular and old open clusters (Kalužny et al. 1995b, 1996a,b). This will make it possible to measure directly stellar masses at the main sequence turn off points in those clusters, thereby leading to more reliable age estimates than those currently available. The on-going searches for detached eclipsing binaries in galaxies of the Local Group will lead to accurate determination to their distances. However, all these very important tasks will require very good calibration which is possible to do only for the nearby, and therefore apparently bright systems. A discovery of any new bright detached eclipsing binary makes the calibration easier and more reliable. The brightest system of this class is β Aurigae (Stebbins 1910). It has a period of 3.96 days, and the amplitude of less than 0.2 magn, and at m ≈ 2 mag it is one of the brightest stars in the sky.

3.5 Pulsating Stars

Pulsating stars vary continuously, so their periods are easy to establish. There are many different types, the best known are long period variables (Miras), Cepheids (population II cepheids are also known as W Virginis stars), and RR Lyrae. Their periods are typically months, weeks, and ~ 10 hours, and their amplitudes are a few magnitudes, somewhat in excess of 1 magnitude, and somewhat less than 1 magnitude, respectively.

The number of these variables declines rapidly for m > 15 mag, probably due to reaching the limit of our galaxy. However, the incompleteness seems to set in already around m ~ 10 mag. The clumpiness in the sky distribution is another indicator that many objects are missing. This shows strikingly in Figure 3. The two square regions with the majority of RR Lyrae stars catalogued in this general direction are 5 degrees on a side - this is a size of an image taken with a Schmidt camera. The apparent distribution of the RR Lyrae variables reveals the type of instrument used in the searches.

All types of pulsating variables are very good standard candles, useful for distance determination, for studies of the galactic structure, and studies of stellar evolution. All would benefit from complete inventories of those variables.

3.6 Novae and Dwarf Novae

Among the many types of cataclysmic variables the novae and dwarf novae are best known. These are binary stars with orbital periods shorter than one day, with one star being a main sequence dwarf transferring mass to its white dwarf companion. Novae explode once every 10^3 - 10^4 years (theoretical estimate) as a result of ignition of hydrogen accumulated on the white dwarf surface. The amplitudes of light variation are in the range 10-20 magnitudes, and the stars remain bright between a week and a year. The source of energy is nuclear.

Dwarf novae brighten once every few weeks to few years, with the amplitude ranging from 3 to 7 magnitudes, and the stars remain bright between a few days and two weeks. The increases in brightness are cause by the enhanced viscosity in the accretion disk around the white dwarf component, and the source of energy is gravitational.
Figure 3: The distribution of known RR Lyrae type pulsating stars in the magnitude range $15 < m < 16$ mag is shown in galactic coordinates. The patchy distribution of known variables is a clear indication of catalog’s incompleteness.

The sky distribution of novae and dwarf novae is clumpy, indicating incompleteness. But there is more than that. Every year new stars are discovered to explode, so the search for new events has no end. The more explosions we observe, the fewer we miss, the better our understanding of the nature of these stars, their origin and their evolution.

3.7 Supernovae Type Ia

A supernova explosion is the end of nuclear evolution of a massive star. This is a very spectacular but very rare event, with the typical rate of about one explosion per century in a galaxy like ours. Among many types of supernovae those of type Ia are most useful as cosmological probes. They are standard candles with peak magnitudes

$$m_{B,\text{max}} \approx 19.1 + 5 \log(z/0.1) = 17.1 + 5 \log(z/0.04),$$

(Branch and Tammann 1992, and references therein). Most of the scatter may be removed using the correlation between the absolute peak magnitude and the initial rate of decline (Phillips 1993). A further result has been obtained by Riess et al. (1995a, 1996), and Hamuy at al. (1995), who found that SN Ia light curves form a well ordered one parameter family, with somewhat different peak luminosities (range about 0.6 mag) and shapes. Even the exponential declines have somewhat different slopes. This work seems to indicate that the scatter in the Hubble diagram of SN Ia in the redshift range $0.05 \leq z \leq 0.10$ can be reduced down to 0.1 mag in V band.

The rate of SN Ia is approximately 0.6 per $10^{10} \, h^{-2} \, L_{B,\odot}$ per century (Table 8 of van den Bergh and Tammann, 1991). The luminosity density in the universe can be estimated with the CfA redshift surveys (de Lapparent, Geller and Huchra 1989) to be $0.8 \times 10^8 \, L_{B,\odot} \, h \, Mpc^{-3}$. These two numbers
can be combined with Eq. (1) to obtain the SN Ia rate for the whole sky:

\[ N_{SN, Ia} \approx 300 \times 10^{0.6(m_{\text{max}}-17)} \text{ yr}^{-1}. \]

As a large fraction of the sky cannot be monitored being too close to the sun, and the weather is never perfect, the maximum effective detection rate is likely to be a factor \( \sim 2 \) lower than that given with the eq. (2). Still, if an all sky variability survey can reach magnitude 17 then over a hundred type Ia supernovae will be discovered every year, providing excellent data to improve the Phillips, Riess et al. and Hamuy et al. relation, and will allow even more accurate study of the large scale flows (Riess et al. 1995b). Also, such a survey would provide a steady stream of alerts of supernovae prior to their maximum brightness, allowing the most detailed follow-up studies with the HST, the Keck, and other large telescopes.

### 3.8 Quasars and other Active Galactic Nuclei

A large fraction of active galactic nuclei (AGN) is variable, some with very large amplitudes. One of the most efficient ways to discover new quasars is a search for variable objects (Hawkins and Vérnon 1993). There are 12 active galactic nuclei listed as variable stars in the General Catalogue of Variable Stars (Kholopov et al. 1988). These were first found and catalogued as variables stars, and subsequently found to be at cosmological distances. The following is the list, with the observed range of magnitudes given in brackets: AU CVn (14.2 - 20.0), W Com (11.5 - 17.5), X Com (15.9 - 17.9), GQ Com (14.7 - 16.1), V1102 Cyg (15.5 - 17), V395 Her (16.1 - 17.7), V396 Her (15.7 - 16.7), BL Lac (12.4 - 17.2), AU Leo (17. - ), AP Lib (14.0 - 16.7), UX Psc (16. - ), BW Tau (13.7 - 16.4). No doubt there are many other bright and variable active galactic nuclei in the sky, and new objects appear all the time. A search for new AGNs as well as a continuous monitoring of those which are already known is very important for our understanding of these enigmatic objects.

### 3.9 Gamma-ray Bursts

One of the main driving forces in the plans for massive photometric searches has been the desire to find optical counterparts (optical flashes) associated with gamma-ray bursts (GRBs, cf. a chapter: Counterparts - General, pages 382-452 in Fishman et al., 1994). This is a very ambitious undertaking. There are two broad approaches. One may wait for a trigger signal from a GRB detector, like BATSE, which provides the exact time and an approximate direction to look at. An alternative is to have a wide field non-stop monitoring of the sky and look later into possible coincidences with GRB detections. In either case the instrument and the data it will generate can be used for the searches of all kinds of astronomical objects as described in this paper.

If a system is to work in the first mode then it would be best to have a GRB detection system which could provide reasonably accurate positions (say better than a degree) in real time for all strong GRBs, as these are the most likely to have detectable counterparts. Unfortunately, BATSE detects only \( \sim 40\% \) of strong bursts and provides instant positions good to \( \sim 5 - 10^\circ \) (cf. Fishman et al. 1992, and references therein). It would be ideal to have small GRB detectors, like the one on the Ulysses planetary probe (Hurley et al. 1994), placed on a number of geo-stationary satellites. Such instruments could provide real time transmission of the information about every registered \( \gamma \) photon, and with a time baseline between the satellites of \( \sim 0.2 \) seconds the positions good to a \( \sim 1^\circ \) could be available in real time for almost all strong bursts. Such a good GRB alert system would put very modest demands for the optical follow up.

In the other extreme, a blind search for optical flashes from GRBs, the demand for the optical system capabilities are very severe, well in excess of any other project mentioned in this paper. It seems reasonable to expect that the very powerful system that may be required, like the TOMBO Project (Transient Observatory for Microlensing and Bursting Objects, Otani et al. 1996), would start small and gradually expand to the data rate \( \sim \text{terabyte per hour} \), along the way addressing most topics presented in this paper.
3.10 Killer Asteroids

While it is possible that global disasters, like the extinction of dinosaurs, may be caused by impacts of large asteroids, such events are extremely rare (Chapman and Morrison 1994, and references therein). On the other hand smaller asteroid or cometary impacts which happen every century may be of considerable local concern. The best known example is the Tunguska event (Chyba et al. 1993, and references therein). In such cases there is no need to destroy the incoming ‘killer asteroid’ in outer space, it is sufficient to provide an early warning of the impact and evacuate the site.

The less devastating events are much more common. There are several multi-kiloton explosions in the upper atmosphere when small asteroids or large meteorites disintegrate, producing very spectacular displays which are harmless (cf. Chyba 1993, and references therein). With a sufficiently early warning such events could be observed and they could even provide considerable entertainment, like the impact of the comet Shoemaker-Levy on Jupiter in the summer of 1994, and the bright comet Hyakutake in the spring of 1996.

An early warning system detecting not so deadly ‘killer asteroids’, or rather cosmic boulders, may be feasible and inexpensive. A mini-asteroid with a diameter of 35 meters ($10^{-5}$ of our moon diameter) would appear as an object of $\sim 13$ magnitude while at the distance of the moon, in the direction opposite to the sun. Moving with a typical velocity of $\sim 10$ km s$^{-1}$ it would reach earth in $\sim 10$ hours. Close fly-byes would be far more common, and such events are currently detected with the Spacewatch program (cf. Rabinowitz et al. 1993a,b, and references therein). If the relative transverse velocity of the cosmic boulder with respect to earth is $10$ km s$^{-1}$ then at the distance of the Moon it corresponds to the proper motion of $\sim 5''$ s$^{-1}$. Of course, it the object is heading for earth then the proper motion is much reduced, as the motion is mostly towards the observer.

According to Rabinowitz (1993a, Fig. 12) one boulder with a diameter of 30 meters collides with earth once per year, and the more common 10 meter boulders do it ten times a year. The cross section to come to earth as close as the moon, i.e. within 60 earth radii is larger by a factor $\sim 60^2 = 3,600$. Therefore, on any given day we may expect 10 boulders of 30 meter diameter and 100 boulders of 10 meter diameter to pass closer to us than our Moon. At their closest approach these are brighter than 13 and 15.5 magnitude, respectively. There may be dozens of nearby cosmic boulders brighter than 16 magnitude at any time. They are the brightest when looked at in the anti-solar direction. If a fair fraction of these could be detected and recognized in real time they would offer a fair amount of excitement. And we would learn about inhabitants of the solar system as well.

Recently, a $\sim 300$ meter diameter asteroid was detected at the distance $\sim 450,000$ kilometers (Spahr 1996, Spahr & Hegenrother 1996). It was expected to be the closest to us on May 19.690, 1996 UT, and to be 11th magnitude at that time.

3.11 Other Planetary Systems, Dark Matter

The first extrasolar planetary system with a few earth-mass planets has already been discovered (Wolszczan and Frail 1992, Wolszczan 1994). However, this is considered peculiar, with the planets orbiting a neutron star. A number of super-Jupiter planets were also found around a few nearby solar-type stars: 51 Peg (Mayor and Queloz 1995), 70 Vir (Marcy and Butler 1996), and 47 UMa (Butler and Marcy 1996). No doubt a detection of earth-mass planets around solar-type stars would be very important. The only known way to conduct a search for earth-mass planets with the technology which is currently available is through gravitational microlensing (Mao and Paczyński 1991, Gould and Loeb 1992, Bennett and Rhie 1996, Paczyński 1996a, and references therein).

This project requires a fairly powerful hardware, $\sim 1$ meter class telescopes, and it has to be targeted in the direction where microlensing is known to be a relatively frequent phenomenon, i.e. the galactic bulge. It is not know how large area in the sky is suitable for the search, and how many stars are there detectable from the ground. An reasonable estimates are $\sim 100$ square degrees and up to $\sim 10^9$ stars. There are various approaches proposed. My preference would be to look for high magnification events with the amplitude of up to 1 magnitude and a duration of $\sim 1$ hour. This
would call for a continuous monitoring program in order to acquire a large number of photometric measurements well covering short events. If we assume that every star has one earth-mass planet then the so called optical depth to microlensing by such planets would be $\sim 10^{-11}$, and it would take $\sim 100$ hours of continuous photometric monitoring of $10^9$ stars to detect a single planetary microlensing event, i.e. up to 20 such events could be detected every year from a good ground based site. Clearly, this project is very demanding in terms of data acquisition and data processing.

Such a search could also either detect dark matter with compact objects in the mass range $\sim 10^{-8} - 10^6 M_\odot$ (Paczyński 1996 and references therein), or place very stringent upper limits.

3.12 Local Luminosity and Mass Functions, Brown Dwarfs

In general, gravitational lensing provides only statistical information about the masses of lensing objects (Paczyński 1996b). However, any very high proper motion star must be nearby, and hence its distance can be measured with a trigonometric parallax. For given stellar trajectory it is possible to predict when the star will come close enough to a distant source (that is close in angle, in the projection onto the sky) to act as a gravitational lens. If the microlensing event can be detected either photometrically (Paczyński 1995) or astrometrically (Paczyński 1996c) then the mass of the lens can be directly measured. The only problem is that in order to have a reasonable chance for a microlensing event the high proper motion star must be located in a region of a very high density of background sources, i.e. within the Milky Way. A search for such objects is very difficult because of crowding. However, once the rare high proper motion objects are found the measurement of their masses by means of microlensing is a fairly straightforward process, as such events can be predicted ahead of time, just like occultations of stars by the known asteroids.

Recent discovery of very faint nearby objects, most likely field brown dwarfs, indicates that there may be a significant population of sub-stellar objects in the galactic disk (Hawkins et al. 1996). A discovery of such objects in the Milky Way would offer a possibility to measure their masses by means of gravitational microlensing. This project, just as the one described in the previous sub-section, is very demanding in terms of data acquisition and data processing rate.

4 Implementation

The searches of various objects described in the previous section cover a very broad range in the required instrumentation. Some, like the search for variables stars brighter than 13 mag, can be conducted with a telephoto with a CCD camera attached to it. Of course, in order to cover the whole sky with such a search dozens or even hundreds of such simple instruments may be needed.

The searches for nearby asteroids do not demand much larger apertures, as many of these are expected to be brighter than 13 mag. However, as they move rapidly a very efficient data processing would be required in order to notice them before they are gone.

The searches for variable stars are useful at any magnitude limit, as the current catalogs are not complete, except (perhaps) for the brightest $\sim 1000$ stars. But some variables are likely to be faint, like supernovae, as they are very far away. It is unlikely that a useful supernova search can be conducted with an instrument with a diameter smaller than about 20 cm. Any project involving a search for microlensing events calls for a $\sim 1$ meter telescope.

A major technical issue facing any massive search is data processing. The experience of the current microlensing searches demonstrated that robust software can be developed to handle billions of photometric measurements automatically (e.g. Pratt et al. 1996). So far such software runs on workstations. However, today’s personal computers are as powerful as yesterday’s workstations, or as supercomputers used to be. Therefore, there is no problem in principle to transfer the know-how to the level of serious amateur astronomers.

Once the local data processing is under control the second major problem is the communication: how to make those gigabytes (or soon terabytes) available to the world? Clearly, the Internet is of
some help, but not at this volume, or at least not yet. The problem of effective distribution of the vast amount of information collected in modern microlensing searches has not been solved yet. No doubt the solution will be found some day, hopefully before too long.

Some steps have already been taken on the road towards this brave new world of massive all sky searches and monitoring. For example the EROS, MACHO and OGLE collaborations provide up-to-date information about their microlensing searches and other findings, and a complete bibliography of their work on the World Wide Web and by anonymous ftp.

There are other projects under way, some of them active for a long time, which are now accessible over Internet. The members of the American Association of Variable Star Observers (AAVSO) were monitoring a large number of variable stars for many decades. The organization is publishing an electronic journal AAVSO NEWS FLASH. An important electronic news system is the Variable Star NETwork (VSNET). Another Internet-based organization: The Amateur Sky Survey (TASS), has the explicit aim to monitor the whole sky with CCD detectors, and to provide full access to all data over the Internet.

Yet another fascinating on-line demonstration what a modern technology can do when combined with a human ingenuity is provided by “Stardial”, set by Dr. Peter R. McCullough at the roof of the astronomy building on the campus of the University of Illinois at Urbana-Champaign. Stardial is a stationary weather-proof electronic camera for recording images of the sky at night autonomously. It is intended for education, primarily, but it may be of interest to astronomers, amateur or professional, also. At the Stardial you will find the growing archive of the data coming from the 8x5 degree field of view camera. The limiting stellar magnitude is $\sim 12.5$, through an approximately R filter bandpass.

The links providing access to all the systems mentioned above can be found at:

http://www.astro.princeton.edu/~richmond/surveys.html

No doubt there are many more groups which are already active, or which are planning massive photometric and/or astrometric searches, and which communicate over the Internet. If you know of any other sites, or groups please let us know, and send e-mail to:

bp@astro.princeton.edu (Bohdan Paczyński),
or to:

richmond@astro.princeton.edu (Michael Richmond).

While the number of new searches increases rapidly, and so does the volume, diversity and quality of data, there are many challenges and many unsolved problems in the areas of data acquisition, processing, archiving, and distribution. The volume of data at some sites is already many terabytes, so there is a need to develop efficient and user friendly “search engines”. There is a demand for new scientific questions which can be asked in the world of plentiful data. The learning curve is likely to be very long. The full power of this new approach to observational astrophysics will be unleashed if monitoring of the whole sky to ever fainter limits, and ever more frequently, can be sustained for an indefinite length of time. However, for that to be possible very inexpensive answers have to be found to all aspects of these projects. Over the years many wonderful programs had been discontinued for the lack of funds. I am optimistic. Just a few examples given above show the magic of the Internet, and they also demonstrate that ingenious people are more important than big budgets.

5 Acknowledgments

I am very grateful to Dr. Michael Richmond for setting up the WWW page with the links to the information about many on-going massive variability searches. This work was supported by the NSF grants AST-9313620 and AST-9530478.

References
[1] Akerlof, C. et al. 1994, Gamma Ray Bursts, Second Workshop, AIP Conference Proceedings 307, eds. G. Fishman, J.J. Brainerd, & K. Hurley, p. 633

[2] Alard, C. 1996a, ApJ, 458, L17

[3] Alard, C. 1996b, in Proc. IAU Symp. 173, p. 215 (Eds. C. S. Kochanek, J. N. Hewitt; Kluwer Academic Publishers, Dordrecht/Boston/London)

[4] Alcock, C. et al. 1993, Nature, 365, 621

[5] Alcock, C. et al. 1995a, Phys. Rev. Letters, 74, 2867

[6] Alcock, C. et al. 1995b, AJ, 109, 1653

[7] Alcock, C. et al. 1995c, preprint: astro-ph/9512146

[8] Allen, C. W. 1973, Astrophysical Quantities, p. 243 (The Athlone Press, University of London)

[9] Andersen, J, 1991, A&AR, 3, 91

[10] Aubourg, E. et al. 1993, Nature, 365, 623

[11] Baliunas, S. & Richard, J. L. eds. 1991, Robotic Observatories: Present and Future, Fairborn Press.

[12] Bennett, D. P. & Rhie, S. H. 1996, preprint: astro-ph/9603158

[13] Boer, M. 1994, private communication

[14] Braeuer, H.-J., & Vogt, N. 1995, "Optical Sky Monitoring: Past and Future", Proceedings of IAU Colloquium No. 151 "Flares and Flashes", Sonneberg, J. Greiner, H.W. Duerbeck and R.E. Gershberg (edts.), Lecture Notes in Physics, Springer, p. 402-406

[15] Branch, D., & Tammann, G. A. 1992, Ann. Rev. Astron. Ap., 30, 359.

[16] Butler, R. P., & Marcy, G. W. 1996, ApJ, 464, L153

[17] Chapman, C. R., & Morrison, D. 1994, Nature, 367, 33

[18] Chyba, C. F. 1993, Nature, 363, 701

[19] Chyba, C. F., Thomas, P. J., & Zahnle, K. J. 1993, Nature, 361, 40

[20] Cook, K. H. et al. 1996, in Proc. IAU Colloquium 155, ASP Conf. Ser. 83: “Astrophysical Applications of Stellar Pulsations”, p. 221 (Ed. R. Stobie)

[21] de Lapparent, V., Geller, M. J., & Huchra, J. P. 1989, ApJ, 343, 1.

[22] Filippenko, A. V. ed. 1992 ASP Con Ser Vol 34: Robotic Telescopes in the 1990s.

[23] Fishman, G. J. et al. 1992, American Inst. Phys. Conf. Proc. 265: “Gamma-Ray Bursts” (Editors: W. S. Paciesas and G. J. Fishman, AIP, New York), p. 13.

[24] Fishman, G. J., Brainerd, J. J. & Hurley, K. (Editors), 1994, American Inst. Phys. Conf. Proc. 307: “Gamma-Ray Bursts” (AIP, New York).

[25] Gould, A., & Loeb, A. 1992, ApJ, 396, 104

[26] Grison, P. et al. 1995, A&AS, 109, 447

[27] Gunn, J. E. & Knapp, G. R. 1993, in “Astronomical Surveys”, (Ed.: B. T. Soifer), ASP Conference Proceedings 43, 267
[28] Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., & Avilés, R. 1995, AJ, 109, 1
[29] Hawkins, M. R. S., & Vérnon, P. 1993. MNRAS, 260, 202
[30] Hayes, D. S. & Genet, R. M. eds. 1989, Remote Access Automatic Telescopes, Fairborn Press.
[31] Hawkins, M. R. S., Ducourant, C., M. Rapaport, M., & Jones, H. 1996, presented at the Royal Astronomical Society's National Astronomy Meeting in Liverpool (reported in Science News, 149, 345)
[32] Henry G. W. & Eaton, J. A. eds. 1995, ASP Conference Series Vol 79: Robotic Telescopes: Current Capabilities, Present developments, and Future Prospects for Automated Astronomy.
[33] Honeycutt, R. K. & Turner, G. W. 1990
[34] Hudec, R. & Soldan, J. 1994, ApJ Suppl. 92, 675
[35] Hurley, K. et al. 1994, Gamma Ray Bursts, Second Workshop, AIP Conference Proceedings 307, eds. G. Fishman, J.J. Brainerd, & K. Hurley, p. 27
[36] Kahužny, J. et al. 1995a, A&AS, 112, 407
[37] Kahužny, J. et al. 1995b, preprint: astro-ph/9511038
[38] Kahužny, J. et al. 1996a, A&AS, in press = astro-ph/9601053
[39] Kahužny, J. et al. 1996b, A&AS, in press = astro-ph/9604027
[40] Kent, S. M. 1994, ApSS, 217, 27
[41] Kholopov, P. N. et al. 1988, General Catalogue of Variable Stars, 4th Edition (Moscow: Nauka Publishing House; available on CD-ROM from NASA Goddard Space Flight Center, Astronomical Data Center, NSSDC: Selected Astronomical Catalogs)
[42] Kimm, H. A. et al. 1994, Gamma Ray Bursts, Second Workshop, AIP Conference Proceedings 307, eds: G. Fishman, J.J. Brainerd, & K. Hurley, pp 423
[43] Mao, S., Paczyński, B. 1991, ApJL, 374, L37
[44] Marcy, G. W., & Butler, R. P. 1996, ApJ, 464, L147
[45] Mayor, M., & Queloz, D. 1995, Nature, 378, 355
[46] Otani, C., Yoshida, A., Kawai, N, Shimizu, H. M., Matsuoka, M., Susukita, R., Ebisuzaki, T., Ohno, Y., Sumouchi, K., Ueno, M., Wada, T., Yamauchi, M., & Takeyama, N. 1996, private communication
[47] Paczyński, B. 1995, Acta Astron., 45, 345 = astro-ph/9504093
[48] Paczyński, B. 1996a, in Proc. IAU Symp. 173, p. 199 (Eds. C. S. Kochanek, J. N. Hewitt; Kluwer Academic Publishers, Dordrecht/Boston/London)
[49] Paczyński, B. 1996b, ARA&A, Vol. 34, in press = astro-ph/9604011
[50] Paczyński, B. 1996c, preprint = astro-ph/9606060
[51] Paczyński, B. 1996d, preprint = astro-ph/9608094
[52] Perlmutter, S. et al. 1992, in: Robotic telescopes in the 1990s; Proceedings of the Symposium, 103rd Annual Meeting of the Astronomical Society of the Pacific, Univ. of Wyoming, Laramie, June 22-24, 1991, (A93-36457 14-89), p. 67

[53] Phillips, M. M. 1993, ApJ, 413, L105.

[54] Pratt, M. R. et al. 1996, preprint: astro-ph/9606134

[55] Rabinowitz, D. L. et al. 1993a, ApJ, 407, 412

[56] Rabinowitz, D. L. et al. 1993b, Nature, 363, 704

[57] Riess, A., Press, W.H., & Kirshner, R. 1995a, ApJ, 438, L17

[58] Riess, A., Press, W.H., & Kirshner, R. 1995b, ApJ, 445, L91

[59] Riess, A., Press, W.H., & Kirshner, R. 1996, preprint: astro-ph/9604143

[60] Ruciński, S. 1994, PASP, 106, 462

[61] Schaefer, B. E. et al. 1994, ApJ, 422, L71

[62] Spahr, T. 1996, Circular No. 6402

[63] Spahr, T., & Hegenrother, C. 1996, reported in Science News, 149, 365

[64] Stebbins, J. 1910, ApJ, 32, 185

[65] Udalski, A. et al. 1992, Acta Astron., 42, 253

[66] Udalski, A. et al. 1993, Acta Astron., 43, 289

[67] Udalski, A. et al. 1994a, Acta Astron., 44, 165

[68] Udalski, A. et al. 1994b, Acta Astron., 44, 317

[69] Udalski, A. et al. 1995a, Acta Astron., 45, 1

[70] Udalski, A. et al. 1995b, Acta Astron., 45, 433

[71] van den Bergh, S., & Tammann, G. A. 1991, Ann. Rev. Astron. Ap., 29, 363.

[72] Wolszczan, A. & Frail, D. 1992, Nature, 355, 145

[73] Wolszczan, A. 1994, Science, 264, 538

[74] Woodward, Ch. E. et al. 1993, ApJ, 408, L37