II. PHOTOMETRIC RESEARCH PROGRAMMES

a) Invited and oral contributed papers.

STELLAR PHOTOMETRY WITH SMALL TELESCOPES

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ABSTRACT. The dominant trend within stellar photometry in recent years has been an increase in the number of intermediate and narrow-band photometric observations, particularly with small telescopes. Recent examples illustrating the scope and emphasis of such programs are reviewed. It is concluded that with continuing improvement in detector technology and telescope automation, small telescope photometry will grow in importance.

1. INTRODUCTION

The goal of stellar photometry is simple. By observing the energy output of a star through a series of well-chosen passbands, one hopes to measure the cumulative distortion of the stellar black-body spectrum by the absorption (emission) features of the stellar atmosphere to obtain the big three of intrinsic stellar properties, temperature, luminosity/ surface gravity, and metallicity. The data can provide a direct probe of stellar structure and evolution and, when combined with extrinsic parameters such as distance, position, and space velocity, allow delineation of the evolutionary history of the ensemble of gas, dust, and stars known as our Galaxy.

Since the postwar period when availability of cheap photomultipliers made photoelectric photometry feasible for the general community, the field has followed a pattern of development familiar among new techniques in astronomy. Initially, broad-band UBV photometry appeared to provide the big three with an accuracy comparable to high dispersion spectroscopy, without the magnitude restrictions and the complex uncertainties of spectroscopic analysis; it helped make the 50's and 60's the golden age of stellar photometry. With time, however, photometry began a steady decline and an increasing shift to smaller telescopes. The related reasons for this are fourfold: (1) there is a sense in the literature that the broad outline of our understanding of stars was complete, and that the remaining work would concentrate on filling in the modest details; (2) it was recognized that broad-band, two-color data were incapable of providing reliable independent information on the big

J. B. Hearnshaw and P. L. Cottrell (eds.), Instrumentation and Research Programmes for Small Telescopes, 135–147.

three; (3) the use of broad-bands oversimplified too much and hid the fine, structural differences among stars which were now important, particularly in the area of metallicity; and (4) improved observational and computational techniques made high dispersion spectroscopy a logical, feasible, and attractive alternative for the study of larger, fainter, stellar samples. It is the purpose of this review to demonstrate that (1) was exaggerated, while (2) through (4) have been overcome, in great measure, by the growing trend toward intermediate and narrow band photometric systems, almost exclusively in use on small telescopes. The latter point is illustrated in Table 1, which shows the distribution of papers published in 1974 and 1984 as a function of photometric system used on small telescopes for nonvariable stars. Between 1974 and 1984, the total number of papers increased by about 30%, the largest group for both years was the UBVRI sample, but intermediate band systems, particularly the uvby system, garnered a growing share of the total, and the total number of photometric systems went from 9 to 14.

Rather than attempt a comprehensive review of all systems and the published work of the last five years, I will concentrate in detail on a handful of programs done predominantly with small telescopes which exemplify the fine, quality research which can be done with smaller instruments, in contradiction with assumption (1) above; section 2 will deal with the broad area of stellar structure and evolution, while section 3 will cover stellar populations. Section 4 will close with a summary, and a discussion of possible future directions for small telescope photometry. It should be emphasized that the choice of which programs to discuss is only partially a reflection of my personal bias; the statistics of Table I partially dictated the emphasis on specific systems. Even so, I apologize to the dozens of photometrists whose excellent work will go unmentioned in the short time available.

Table I

Distribution of Papers by Photometric System

System	1974	1984	System		1974		1984
UVBRI	54%	42%	DDO		4%		2%
IR	11%	9%	Geneva		1%		4%
uvby Hβ	10%	23%	Others	(2)	3%	(7)	8%
Vilnius	9%	5%					
RGU	8%	7%	N TOTAL		109		138

2. STELLAR STRUCTURE AND EVOLUTION

2.1 Star Formation

One of the least understood stages of a star's life is the way it forms. While the earliest stages of the process when the protostar is shrouded in a thick cloud of gas and dust are studied optimally with IR and longer wavelength observations, some crucial insight can be gained by optical observations made as the star emerges from its opaque cocoon. Of primary interest are the related questions of the large scale relationship among individual star forming regions within an extended cloud complex, and the factors controlling the formation timescale and mass function within the clouds.

An ideal testing ground for current theories is the region of the CarOB1 complex containing the open clusters Tr14, Tr15, Tr16, Cr228, NGC3324, NGC3293, and IC2581. From UBVRI, uvby Hβ, and Walraven photometry, and classification spectroscopy of individual clusters (Turner et al. 1980 and references therein--hereafter TGHH), there is little doubt that all the clusters lie at the same distance. When uniform age estimation is applied to all the clusters, as in TGHH (see Fig. 10 of their paper), a very obvious pattern emerges. The clusters are strung along a line parallel to the galactic plane over a distance of 150 pc., with an age gradient where the older subgroups are at lower galactic longitude. While this qualitatively agrees with the Elmegreen and Lada (1977) theoretical picture of sequential star formation and the observations of nearby associations such as Orion, the quantitative analysis shows several nagging discrepancies. The age spread (5 x 10^6 years) appears to be far too small, and the individual subgroups are much richer in members than expected. A closer look at a member of the oldest subgroup (NGC3293) reveals even more problems.

The reddening corrected CMD for NGC3293 (Fig. 6, TGHH) shows a well-defined upper main sequence with a turnoff in the early B star range, but is discrepant in two ways. Four stars near the tip of the main sequence are in anomalous positions for the cluster age, while three faint, cool stars are located near the main sequence with a predicted age that's three times larger than the cluster turnoff age. While it is easy to dismiss the discrepant stars as statistical aberrations, the follow-up work by Herbst and Miller (1982,HM) has emphasized just how important they are. With photographic plates from a 0.6m, a CMD to V=16 was constructed of the cluster environs. It shows a main sequence populated to, at least, Mv=2.8, or M=1.4 M$_\odot$ with a potential pre-main sequence at fainter magnitudes. The pre-main sequence contraction age implies a cluster age of 20 x 10^6 years, three times larger than that from the main sequence turnoff. When taken in the context of the earlier work on NGC2264 (Warner et al. 1977), h and χ Persei (Vogt 1971), and the Pleiades (Landolt 1979), the implication is inescapable. Coeval star formation in clusters is a myth. Either the theoretical timescales for pre-main sequence evolution are seriously in error, or low mass stars in clusters form first. From the work of Stauffer (1982) on the Pleiades, where the age spread is about 3 x 10^8 years, it can be inferred that the formation of low and high mass stars occurs in two distinct phases, or the stars which form at any given time cover a specific mass range, with the mean mass increasing with time; in either case, at the low mass end, star formation is not a continuous process. At the high mass end, there is some evidence for continuous star formation. In agreement with the above results on NGC3293, Jackobsen (1984), from uvby Hβ data of hundreds of B stars covering the mass range of 2.5 to 13 M$_\odot$ in nearby open clusters, has found age spreads within individual clusters of between 10^7 and 10^8 years. Similar conclusions have been drawn from the composite CMD studies of Mermilliod and Maeder (1984).

Two questions immediately come to mind. What is the mechanism for mass-dependent, star formation delay in molecular clouds, and, if star formation is a discontinuous process, where does the break or over-lap in mass for the two phases occur?

Two relevant observational points are that many of the younger, well-studied open clusters exhibit extended halos populated predominantly by low mass stars (HM and references therein) and mass functions deficient in low mass stars compared with the field (Van den Bergh and Sher 1960; HM). While similar results for older clusters are invariably interpreted as the effect of dynamical mass segregation, in younger clusters the distribution is explained best as a fossil record of the initial star formation distribution. From the analysis by HM, one can conclude that the classical fragmenting protocloud picture of star formation, controlled by the Jeans' mass, is no longer supported by the observations, in agreement with recent theoretical approaches. The paucity of low mass stars removes the model of Norman and Silk (1980), but is consistent with the theoretical predictions of Larson (1982, 1985). After compressing into sheets, cloud fragmentation occurs because of the gravitational instability of the sheet, with the minimum protostellar cloud size controlled by the temperature of the gas. This naturally leads to sequential mass formation, with a lower mass cutoff growing with time as the temperature of the gas rises due to the appearance of higher mass stars. The significance of these models is difficult to overestimate. Larson (1985) outlines the effects of making star formation a bimodal process, analogous to a picture presented by Eggen (1976), where the peaks of the two distributions in the mass function are allowed to change with time and position in the Galaxy. As also noted by Gusten and Mezger (1982), an appropriately parameterized mass function can explain the dip in the luminosity function of nearby stars at $M=0.7\ M_\odot$, the unseen mass in the solar neighborhood, chemical evolution of the disk without infall, the steep Galactic abundance gradient, and the mass-to-light ratios, colors, and gas contents of spiral galaxies, along with a variety of other galaxy parameters.

If even partially correct, the above would imply that the notion of a universal mass function over the entire mass range is invalid. One should be able to find star-forming regions where only higher mass stars have formed, as in the core of Orion, while in others, such as Taurus, the mean mass of the stars in formation will be significantly lower. Additional observations of the type noted above are needed to clarify such questions as what variables control the relative strength of the two modes in associations vs. clusters, what mass range of stars determines the sequential star formation initiation process across an extended cloud complex, and over what range of scale does the pancake picture of the cloud collapse extend?

2.2 Up, Down, and In Between

Besides demonstrating the effects of time-dependent star formation on the structure of the CMD, precise photometry can be used as a probe of the effects of varying internal structure on a star's surface properties. Comparisons between theory and precision observations provide exquisite tests of just how realistic and complete our picture of stellar astrophysics and the variables which influence it are.

The first such confrontation of theory with observation has already been partially discussed in 2.1. Studies of luminous, high mass stars within galactic associations (Humphreys 1978) and within the field (Garmany, Conti, and Chiosi 1982) reval that these stars exhibit the same spread in the CMD as found by Jakobsen (1984). In contradiction with the predictions of stellar evolution theory (Maeder 1984), these stars populate the CMD redward of the termination point of the hydrogen core burning evolutionary models in large numbers. Because of the important role played by these stars in galactic nucleosynthesis, their apparent sensitivity to local initial conditions, and the ease with which they are observed in other galaxies (Conti 1984, Maeder 1981), the observational constraint imposed on current theory by the existence of a wide main sequence has both disturbing and far-reaching impact. Bertelli et al. (1984) find that only limited combinations of mass loss, convective overshoot, and opacity enhancement can reproduce the effect to date.

Moving to slightly cooler, late type B stars, we find our first example of a down point in the stellar distribution, a gap region where the CMD is underpopulated either because of some internal structural discontinuity and/or a rapid evolutionary phase. The gap is easily seen in the two-color diagram on the Geneva system in Mermilliod (1976) where it is also demonstrated that the position of the gap changes as the stars evolve. The gap was emphasized by Eggen (1976) who felt it represented the breakpoint between the two modes of star formation. He also noted, in support of his suggestion, that the brightest stars below the gap had a high rate of spectroscopic peculiarity of the type associated with circumstellar shells, presumably because these stars were still evolving toward the main sequence (see also Turner 1982). To date, no satisfactory explanation has arisen for the source of this feature.

Moving to even cooler regions of the F stars, we find further evidence for main sequence widening with a twist. uvby observations of the intermediate age cluster NGC 752 by Twarog (1983) show the existence of a bimodal main sequence separated in color by 0.03 to 0.04 mag in b-y. The availability of c1 rules out binaries, leaving rotation or two episodes of star formation as logical explanations. The age difference required is 3 x 10^8 years. Evidence that this is not an isolated case comes from a uvby study of NGC 3680, by Nissen (1985, private communication) as shown in Fig. 1. Preliminary results on IC4651 using a CCD show only weak evidence for the effect, if any, despite the fact that it should be the same age. Likewise, a uvby$H\beta$ study of M67, twice the age of NGC752, by Nissen, Twarog, and Crawford (1985) shows the main sequence below the hydrogen exhaustion phase gap to be no wider than 0.015 mag in b-y, (Fig. 2). What is found is that the stars above the gap delineate a blueward hook which is between 0.04 and 0.07 mag wide in b-y; the shape of the turnoff does not agree well with

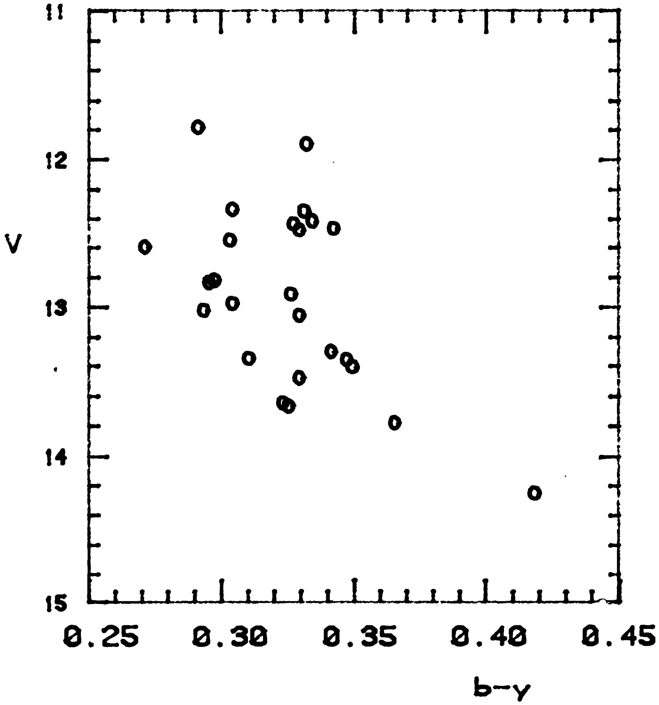

Fig. 1
uvby CMD of
NGC 3680
(Nissen 1985)

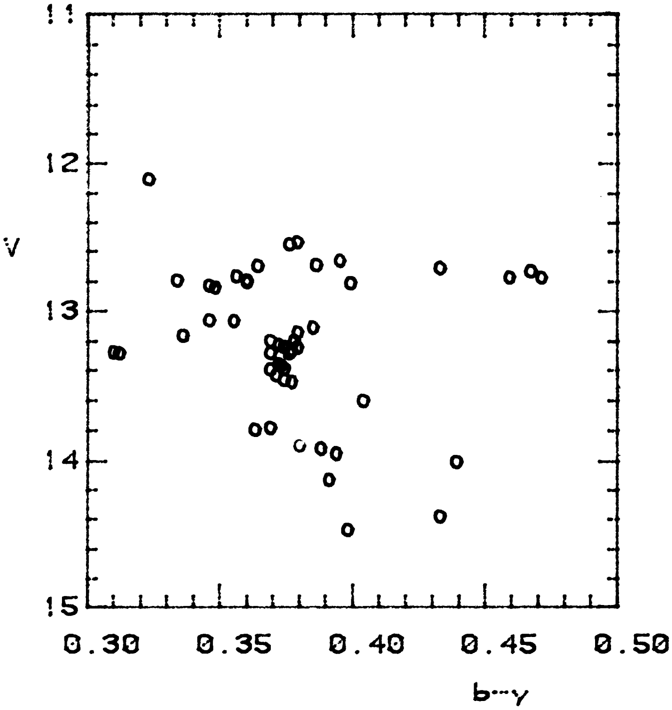

Fig. 2
uvby CMD of
M67 turnoff

the recent isochrone fits by VandenBerg (1985). The nature of the bimodal sequence and the blueward hood in M67 remain unexplained at present, though it has been noted that the Bohm-Vitense-Canterna gap does occur in the temperature range of the former. It is also worth noting that the significance of these effects would not have been recognized without a means of testing for composite systems. The work of Carney (1982, 1983) on photometric detection of unequal component binary systems deserves wider application for field star analysis.

Finally, we turn to low mass stars in the post main sequence phase. Photographic surveys of the giant branches of globular clusters show the presence of a 0.2 mag gap in the giant branch one magnitude above the turnoff in NGC 6752 (Cannon and Lee 1976), ωCen (Da Costa and Villumsen 1982), and NGC 288 (Buonanno et al. 1984). The existence of this gap is not predicted by standard theory, though an ad hoc method of inducing a gap has been proposed by Armandroff and Demarque (1984). The picture has become even more confused with the luminosity function study of the giant branch of 47 Tuc by King, Da Costa, and Demarque (1985). Their photographic work shows that the above gap does not exist in 47 Tuc, but an expected luminosity peak does. The peak reflects the passage of the H-burning shell through a composition discontinuity, and its luminosity location is dependent upon metallicity, helium content, and stellar mass. As in NGC 362, the peak in 47 Tuc is fainter than predicted, indicating that convective overshoot on the subgiant branch is not an insignificant effect as is often assumed in standard models. Further observations are needed.

3. STELLAR POPULATIONS AND GALAXY EVOLUTION

3.1 The Solar Neighborhood

Mould (1982) has defined a stellar population as "a collection of stars of similar age, composition, and kinematics." Implicit in such a definition is the hope that the three properties are uniquely correlated in a way which provides information about the evolution of the Galaxy, rather than in a random distribution, which tells little. Because of the need for reliable space velocities, distances, and stellar parameters, there is no better sample for such a program than the stars nearest the sun, and no better way to study them than with a small telescope. Over the last 40 years, no individual has devoted more of his time to just this approach than Olin Eggen. It would be an easy matter to spend not only the entire talk, but the entire conference discussing just his work; in the last five years alone he has published over 50 papers on the topic. For the sake of time, however, let me discuss only one area of recent research with which he is undoubtedly most associated, and apologize to Olin for mentioning only a minute fraction of his contributions to small telescope photometry.

A key concept in Eggen's analysis of the solar neighborhood is that of moving groups (Eggen 1970 and ref. therein). As star clusters evolve with time, they slowly dissolve into an annular distribution because of the combination of internal velocity dispersion and interaction with the galactic disk. Though difficult to recognize because of their low density, such groups should have essentially the same V velocity at a given galactocentric location and be recognizable from their common motion. From the group V, proper motion measures, radial velocity data, and position, one can derive a distance. In this way, Eggen has identified over a half dozen young stellar groups, and a smaller number of older groups extending through the old disk and into the halo. There is little doubt that the younger groups are real, and the more extreme characteristics of the others have made membership likely, e.g. the HR 1614 group should contain stars significantly above the Hyades in metallicity, a prediction confirmed with DDO photometry by Smith (1984). Others, like the Wolf 630 group, may be questionable (McDonald and Hearnshaw 1983).

Eggen (1983, 1985 and references therein) recently has expanded this concept in two ways. One of the groups (Pleiades), through the extensive use of intermediate band photometry and all available space velocity information, has grown to the scale of a local association containing α Persei, IC2602, NGC2516, Sco-Cen and Lup-Cen associations, and possibly M34. Though comparable in age, there is evidence for an age spread among the luminous stars on a scale of 5×10^7 years, while the fainter main sequence stars show ages closer to 2×10^8 years. The size of the association is about 100 pc.

A similar expansion has occurred for two of the older groups, where Eggen has found evidence for a Hyades supercluster and a Sirius supercluster. We can use the results for the Hyades supercluster to emphasize the importance of this concept, if it is correct. First, assuming group membership, one can obtain reliable absolute magnitude information for stars which are normally beyond the limits of trig parallax. Second, the expanded sample allows one to more accurately map out the pattern of post-main sequence evolution compared to poorly populated open clusters, providing luminosity and mass information on stars rarely found in nearby open clusters. For the Hyades, Eggen (1985) has extended the red giant branch to Mbol = -5, identified the AGB, and found two C star members of the supercluster. A survey of nearby white dwarfs showed 20% to be members of the Hyades, including two very hot stars, F24A and V417 Tau B, the nucleus of a planetary nebula, and a half-dozen cool white dwarfs with cooling times greater than the age of the cluster, among others. A group of stars with very active chromospheres and white dwarf companions has been shown to lie about 0.8 mag above the main sequence. Third, the paucity of old disk clusters and nearby globulars makes the study of old disk and halo groups like Arcturus and Kapteyn's star invaluable, especially on the lower main sequence where age estimation for random field stars is normally impossible. Finally, the surveys of these groups complement the more traditional approach for finding nearby members of the Hyades by Upgren, Weis, and Hanson (1985 and references therein) and emphasizes the fact that the solar neighborhood may not be a representative sample of the Galactic disk chemically or kinematically. It is estimated that one-third of the bright B stars may be members of the Local Association, while 15% of the cooler stars could be members of the Hyades supercluster. Such considerations are rarely, if ever, included in analyses of specific stellar types based upon nearby stars. Further evidence for local anomaly is provided by the reddening studies of Perry et al. (1982), who find the sun to be located in a dust free region at least 75 pc. in radius.

3.2 Beyond the Solar Neighborhood

Over the last ten years, it has been increasingly obvious that our picture of galactic chemical and dynamical evolution is grossly distorted through oversimplification and biased data samples (e.g. Norris, Bessell, and Pickles 1985). The chemical history of the Galaxy is constrained uniquely by the age-metallicity relation, the star formation history, and the observed stellar metallicity distribution. Attempts at the first and third constraints in the 70's were dominated by too small samples (e.g. Pagel and Patchett 1975), inadequate knowledge of the scale height history of the disk, and large uncertainties in individual age determination. Recent attempts using larger samples and uvbyHβ photometry (Mayor 1976, Twarog 1980 and ref. therein) have produced more reliable estimates of the AMR, but the remaining two constraints are still uncertain. Ongoing programs, hold the promise of an order of magnitude improvement in both cases. Olsen (1983) has completed his awesome survey of almost 15,000 stars on the uvby system earlier than G0 down to V=8.3, and age analysis should provide hundreds of stars per billion years within the old disk sample. Radial velocity observations are in progress for over 4,000 of these. Likewise, Ardeberg and Lindgren (1985) are completing a comparable program on cool stars involving photometric observations of 4,000 stars and radial velocity observations of over 2,000. The final constraint, the scale height history, is currently under attack by a variety of groups including Adamson et al. (1985), Twarog (1984), and the Danish group using uvby data on A and F stars, and Grenon and Mayor (1985, private communication) using Geneva photometry of late type stars. These programs should clarify the questions concerning the existence of a thick disk, the abundance gradient, and the nature of the high velocity metal-rich population found in the K-giant survey of Hartkopf, Yoss, and Neese (1985, private communication). The relationship between the high-velocity early type stars and the thick disk remains uncertain (Pier 1982, Stetson 1981). The large radial velocity and photometric surveys by a number of groups (e.g. Carney and Latham 1985) have already produced significant revisions of our knowledge of halo kinematics with more surprises expected.

Finally, we close with a discussion of a direct link beyond the Galaxy, the extragalactic distance scale as defined by the Cepheids. Two programs deserve special note because of their scope and precision. The traditional technique of finding distances to Cepheid clusters through main sequence fitting has long been plagued by field star contamination, binaries, variable reddening, inadequate numbers of stars, and evolutionary effects. Because of the almost vertical nature of the main sequence in the B star range, small errors in photometry led to large discrepancies in distance moduli. These difficulties have been greatly reduced through the use of uvbyHβ photometry by Schmidt (1984 and ref. therein) to observe the Cepheid clusters, and by Balona and Shobbrook (1984 and ref. therein), using the extensive cluster observations of Shobbrook to recalibrate the uvbyHβ system for early type stars, avoiding the use of association stars. The result is inescapable; for the most reliable cluster data, the standard Cepheid scale is shown to be off by 0.4 to 0.6 mag in the sense of providing too bright a luminosity for the Cepheids.

4. SUMMARY, CONCLUSIONS, AND SPECULATION

Having completed our selective survey of the recent photoelectric literature, one might ask what it is that makes these programs exemplary of the type of research best done with a small telescope?

First, there is an implicit assumption that our picture of stellar astronomy is woefully incomplete, and that a good deal of our currently accepted wisdom will end up in ten years as scientific mythology. Within the magnitude limits of a 36 in. telescope, every star in the HD Catalog is observable with any intermediate or broad band photometric system. Since fewer than 10% of these stars have been observed on any system but UBV, it appears difficult to accept that nothing important remains to be learned.

Second, the programs discussed were science driven. They were well-defined and had specific goals in mind which, when obtained, would have an immediate impact upon one or more areas of stellar or galactic evolution. In the area of stellar photometry, too often programs are designed around the need of filling telescope time with the only readily available, easily operated and maintained equipment, a photometer.

Third, the photometric aspect of the programs represents only one component of a more comprehensive project involving high or low dispersion spectroscopy, radial velocities, proper motions, and every other technique in observational astronomy. Photometry is a tool, one tool, which has its specific areas of application and advantage, whether it be on a small or a large telescope. Its speed, efficiency, and precision make it too valuable an approach to exclude from any observational arsenal.

Fourth, if there has been one unifying theme of this talk, it's that the type of project that small telescope photometry serves best is one where crucial trends are hidden in the noise of previously inadequate statistical samples. Often small telescopes are the only option available for such large demands on telescope time.

With these points in mind, what are the likely future directions for small telescope photoelectric research? Let me close by emphasizing only one area of fundamental research and two technical changes. Because of the growing trend toward intermediate and narrow band photometry, and the likelihood of dramatic results from many of the ongoing programs over the next few years, the strong possibility exists that stellar photometry will undergo a modest renaissance, with the concommitant increased demand for larger telescope time, especially in support of space astronomy from Hipparchos (Grenon 1985) and Space

Telescope. One of the greatest shortcomings of the newer systems has been the lack of a large, consistent set of fainter standards for use with larger apertures. Over the years the community has been fortunate to have the dedicated services of individuals such as Landolt, Graham, Cousins, and their coworkers in expanding the availability of broad band standards. It is work for which they have received far too little credit and only modest support. If the newer systems are to have a greater impact, they require the same dedication from their promoters to expand their use.

The need for improved standards is also linked to two technical advances which should change the face of photometry over the next ten years. Since they are both topics of other talks at this meeting, I will only mention them as a plug for the speakers. The first is the development of automated photometric telescope systems (APTS - Genet, this volume). The increased speed, efficiency, and reliability of this approach are too great for it to be ignored as an amateur endeavor, especially in view of the extraordinarily low cost of these systems. The second is the changeover to CCD's (Walker-this volume). They represent such a quantum improvement over photomultiplier photometry that, with a modest decrease in cost, they will make conventional photometry obsolete for most applications. As an example, if these two advances were combined, one person with a few weeks of small telescope time would have the capability of entirely redefining a standard photometric system in terms of CCD observations, single-handedly superceding years of work by a large number of observers using single channel systems. In short, there is every reason to view the future of small telescope photometry with both optimism and excitement. The best is yet to come.

It is a pleasure to acknowledge travel support to this meeting from the International Travel Grant Program of the AAS, and from the IAU. Part of the research discussed was carried out by the author under NSF grant AST-8302091.

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DISCUSSION

Garrison: In your diagram of halo stars, were those mostly giants?

Twarog: Yes.

Garrison: In Delhi, we managed to push through a resolution requesting time assignment committees to allocate time for the establishment of faint standards so that large telescopes can be used more effectively in cases where neutral density filters are not appropriate - e.g. space telescope.

Graham: Do you have any comment about the relative merits of the various intermediate-band photometric systems for detecting such quantities as the metallicity of a star?

Twarog: While I have a bias toward the Strömgren system, I feel that it is important for the originators of a system to promote and explain its application to potential users by publication of first-class scientific results. The best way to attract users is by showing how much high quality research one can do with a system.

McCarthy: Would you please justify your statement about the number of objects observed in the Strömgren and in the Geneva systems? Could you give some numbers please.

Twarog: I feel that the importance of a system is not measured by the number of stars observed on it, but by the application and interpretation of the data. The Strömgren system has produced far more valuable scientific interpretation than the same number of stars observed in the Geneva system.